LECTURES

ON

POWERING AND PROPULSION

BY

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for

3rd. Year - Naval Architecture & Marine Engineering Students

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POWERING OF SHIPS

Introduction :

When a ship moves through water at a certain speed , she experiences resisting forces due to water and air . These resisting forces must be overcome by a thrust - producing mechanism . This mechanism is mostly a PROPELLER .

The convergence into screw propellers was the last step in long and hard centuries of human inventions towards the development of sea transport systems .

Oars and sails were the first elements in propulsion series followed by paddle wheels until about 1845 , when the first screw propelled English steamer " Great Britain " entered into service. From that time the screw propeller has reigned supreme in the realm of marine propulsion .

Although the paddle wheels were still used for a long time after 1845 , they proved less popular than the screw propeller due to the following:

1. While the screw propeller is well protected from damage, the paddle wheel is projected outside the hull which makes it liable to damage in rough seas , also , the immersion of the paddle wheel varies with displacement and the wheel comes out of water during rolling causing erratic course keeping .

2. The paddle wheel increases the overall width of the ship and increases the resistance of the ship, while the propeller has not such defects .

3. The paddle wheel is generally less efficient than screw propeller .

4. The paddle wheel must be driven at low RPM , that requires a big and heavy machinery .

For the a.m. reasons, it can be said that there is no real competitor to the screw propeller .

Propelling Machineries.

The propeller , whatever its type , needs an engine to provide it with the necessary power for rotation , the propelling machinery may be one of the following :

1. Steam Engines.
2. Internal combustion or Diesel engines,(constant torque). This type of engines is divided into groups according to the speed of the engine as follows :

   a. Slow speed engines
   directly coupled to propeller, and use low quality fuel but the size and weight of the engine are bigger than other types .

   b. Medium speed and high speed engines :
   Geared coupled to propeller , and use light fuels , but the size and weight of the engine are less than slow speed engines .

3. Marine Turbines .
   This type of engines is a high fuel consumer , with a high number of rotation , used mainly in war ships where the economy meets less concern .

Factors Influencing the Choice of Propelling Machinery :

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1. Weight and size of engine ,
2. Cost and reliability ,
3. Fuel consumption and cost of upkeep , and
4. Suitability for the ship and propeller .

Marine Ratings :

Rating Definitions :
Ratings are based on ISO 8665 Conditions (100 Kpa , 25^{o}C , and 30% relative humidity)

1. Continuous Duty (CON)
   The continuous duty engines are those intended for continuous use requiring uninterrupted service at full power . Typical application include : ocean going displacement hulls such as fishing trawlers , merchant ships , tugboats , towboats and all ships requires uninterrupted power operation .

2. Heavy Duty (HD)
   The heavy duty engines are those intended continuous use in variable load applications where full power is limited to eight hours out of every ten hours of operation. Also , reduced power operation must be at or below 200 rpm of the maximum rated RPM (medium speed engines) . [5000 hours/year]
   Typical vessel applications include : mid-water trawlers ,ferries , crewboats .

3. Medium Continuous Duty (MCD)
   The medium Continuous Duty Engine are those intended for continuous use in variable load applications where full power is limited to 6 hours out of every twelve hours of operation. Also , reduced power operation must be at or below 200 rpm of the maximum rated RPM (Medium speed engines) ,[3000 hours/year].
   Typical vessel application include : Planning hull ferries , fishing vessels designed for high speed to and from fishing grounds , off-shore service boats , yachts ,and short trip coastal freighters

4. Intermittent Duty (INT)
   The intermittent duty engine are those intended for intermittent use in variable load applications where full power is limited to two hours out of every eight hours of operation . Also , reduced power operation must be at or below 200 rpm of the maximum RPM , [1500 hours/year].
   Typical vessel applications include custom boats , police vessels , pilot boats .

5. High Output (HO)
   The high output engine are those intended for use in variable load operation where full power operation is limited to one hour out of 8 hours operation .
   Also , reduced power must be at or below 200 rpm of the maximum rated RPM .
   [300 hours/year] .
   Typical vessel applications include: pleasure crafts and sport fishers .

POWER DEFINITIONS:

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1. Indicated Power (Steam engines) P_I .

The power of steam engines is determined by measuring the steam stress cycle in the cylinder . This power is called the indicated power .

$$P_I = P.L.A.N / 1000 \quad K.W$$

P = Pressure intensity (Pa)
L = Length of stroke (m)
A = Area of piston
N = Number of revolutions (rps).

2. Brake Power (Internal combustion engines) P_B .

The power measured at the fly wheel of internal combustion engines outside the cylinder by means of mechanical or electrical brake is called the brake power .

$$P_B = M . 2 \pi n / 1000 \quad K.W.$$

M = Engine torque (N.m)
n = rps

3. Shaft Power, P_S (Turbines and Diesel)

The power measured at the tail shaft close to the propeller is called the shaft power .
In diesel engines it is determined from the brake power by reducing bearing , transmission , gearing and mechanical losses .

4. Delivered Power (Developed Power) P_D .

It is the power actually delivered to the propeller , it is somewhat less than the power measured at the tail shaft due to the losses in stern tube bearing and the bearing between stern tube and the position where the shaft power is measured .

5. Thrust Power , P_T .

It is the power developed by the propeller thrust at the speed of advance Va .

$$P_T = S . Va /1000 \quad K.W.$$

6. Effective Power , P_E .

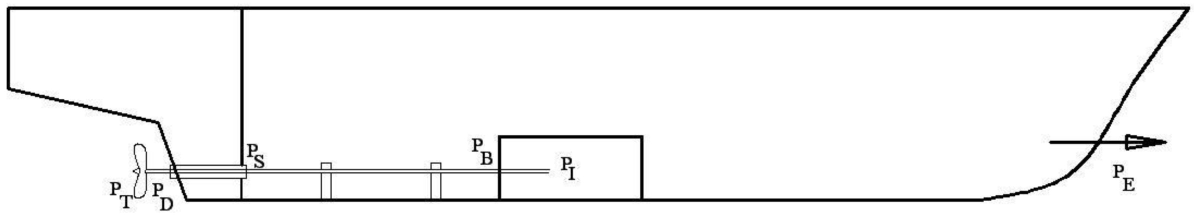
It is the power required to tow a ship at a constant speed V without its propulsive device .

$$P_E = R . V /1000 \quad K.W.$$

R = Ship's total resistance .

$$P_T < P_D < P_S < P_B$$

Locations of Powers Measurement



PROPULSION EFFICIENCIES

The efficiency of any engineering object is defined as the ratio between the useful power output and the input power into the system .

1. The Open Water Efficiency of Propeller η_o

It is the ratio between the power developed by the thrust of the propeller and that absorbed by propeller when operating in open water with uniform inflow velocity Va .

$$\eta_o = P_T / P_D = S . Va /(2 . \pi. n) . M_o$$

M_o = the torque in open water

2. The Behind Efficiency η_B

It is the ratio between the power developed by the thrust of propeller and that absorbed by the propeller when operating behind a model or ship .

$$\eta_B = P_T / P_D = S . Va /(2 . \pi. n) . M$$

M = the torque in behind condition .

3. The Relative Rotative Efficiency η_R

It is the ratio between propeller efficiency behind the hull and the efficiency in open water .

$$\eta_R = \eta_B / \eta_o = M_o / M$$

4. Transmission Efficiency η_t

It is the ratio between the delivered power to the propeller and the shaft power .

$$\eta_t = P_D / P_S$$

5. Hull Efficiency η_H

It is the ratio between the useful work done on the ship and the work done by the propeller .

$$\eta_H = P_E / P_T = R . V / S . Va$$

6. Quasi-Propulsive Efficiency η_D

It is the ratio between the useful power or effective power and the power delivered to the propeller .

$$\eta_D = P_E / P_D = \eta_o \ \eta_R \ \eta_H$$

7. Propulsive Efficiency η_P

It is the ratio between the useful power and the shaft power .

$$\eta_P = P_E / P_S = \eta_o \ \eta_R \ \eta_H \ \eta_t$$

8. The Overall Propulsive Efficiency $\eta_{o.a}$

It is the ratio between the effective power and the brake power , the gearing and mechanical losses are considered .

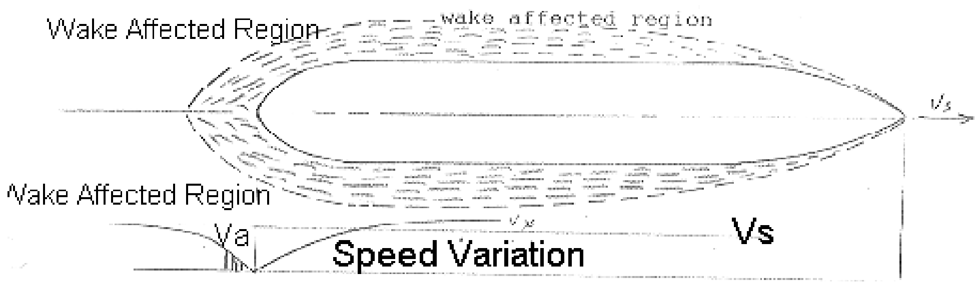
$$\eta_{o.a} = P_E / P_B = \eta_P \ \eta_G \ \eta_m$$

$$= \eta_o \ \eta_R \ \eta_t \ \eta_H \ \eta_G \ \eta_m$$

η_G = the gearing efficiency
η_m = the mechanical efficiency

INTERACTION BETWEEN HULL AND PROPELLER

The wake phenomenon :



The wake is the phenomenon of dead water behind the ship . The wake speed is the difference between the ship speed Vs and the speed of advance Va.

<u>The wake components:</u>

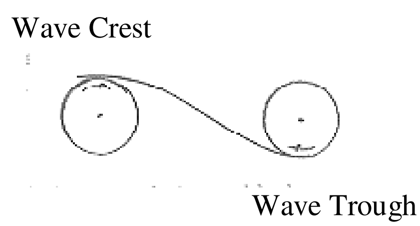
The wake can be split up into three components :-

1- Potential wake :

It is the wake obtained if the ship moves in an ideal fluid without friction and wave making .It is influenced by form of stern (full , U shaped), increased pressure and decreased speed.

2 - Wave wake :

It is the wake component origination from the movement of the water particles in the gravity waves .The orbital motion may be added or reduced from the wave depending on whether a crest or trough of wave is existing .



3 - Frictional wake :

It is the wake created due to friction . It depends on the thickness of boundary layer and speed distribution through it . The loss of kinetic energy of water particles resists the homogeneity of flow behind the ship .

The wake fraction w :

The wake speed (Vs - Va) as a fraction of ship's speed is called the wake fraction .

$$w = (Vs - Va) / Vs$$
$$Va = Vs (1 - w)$$

w is called Taylor's wake fraction .

Froude expressed the wake speed as a fraction of speed of advance .

$$w_f = (Vs - Va) / Va$$

$$Va = Vs / (1 + w_f)$$

The more popular wake fraction is Taylor's (w) .

Directional inequalities of wake :

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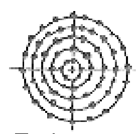
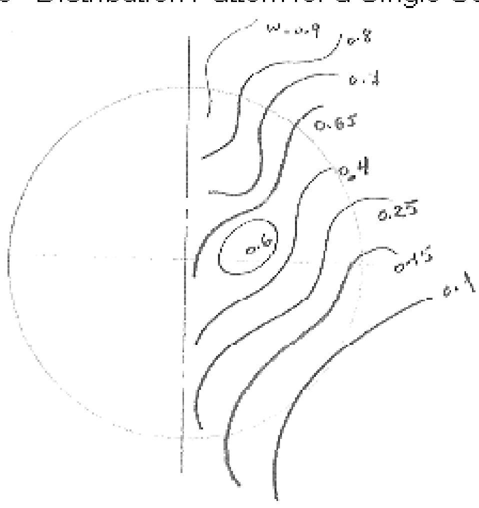
1 - Circumferential inequality of wake .
2 - Radial inequality of wake .
3 - Axial inequality of wake .

The circumferential and radial components are the important ones ,they are measured by Pitot tubes located in the screw disc .
If the measuring devices located in absence of propeller ,the measured wake will be the Nominal wake , while if in presence of propeller it will be the Effective wake .
The distribution of wake speed after being measured , integrated throughout the disc area and divided by the area , gives the mean effective wake .



Measuring Points on Propeller Disc

Typical Wake   Distribution Pattern for a Single Screw Ship



The propeller design depends primarily on the wake distribution in the disk of propeller .
The open water charts of propeller series were made on the basis of the homogeneous wake distribution (w = constant) .
The determination of (w) for preliminary design purposes may be performed using approximate formulae .

1 - Taylor's : $w = 0.5\ Cb - 0.05$ 1910 Single screw ship
$w = 0.5\ Cb - 0.10$ 1923
$w = 0.55\ Cb - 0.2$ Twin screw ship

2 - Heckscher : $w = 0.70\ Cp - 0.18$ Single screw ship
$w = 0.70\ Cp - 0.30$ Twin screw ship
$w = 0.77\ Cp - 0.28$ Trawler
These formula for normal cargo ships at $0.54 <= Cb <= 0.84$

3 - Schoenherr : (single screw)

$$w = 0.1 + \frac{4.5\ (Cb\ .\ Cp\ .\ B\ /\ CWL\ .L)}{(7 - 6\ Cb/CWL)(2.8 - 1.8\ Cp)} + 0.5(E/T - D/B - K.\varepsilon)$$

E = height of propeller shaft above base line .
ε = rake angle (radians) .
K = coefficient which has a value 0.3 for normal types stern and 0.5 to 0.6 for sterns with cutaway deadwood.
D = Propeller diameter

4 - Schoenherr : (twin screw):

a. With bossing and outboard turning propellers .

$$w = 2.0\ .\ Cb^5\ (1 - Cb) + 0.2\ Cos^2\ (3/2\ \varphi) – 0.02$$

b. With bossing and inboard turning propellers .

$$w = 2.0\ .\ Cb5\ (1 - Cb) + 0.2\ Cos^2 (3/2(90 – \varphi) + 0.02$$

φ = angle of bossing to horizontal

c. Propellers supported by struts .

$$w = 2.0\ .\ Cb^5(1 - Cb) + 0.04$$

5 - Schoenherr : For tugs with $0.47 <= Cb <= 0.56$

Single screw $w = 1/3\ Cb + 0.01$
Twin screw $w = 1/3\ Cb - 0.03$

6 - Robertson : $w = 0.45\ Cp - 0.05$

7 - Gill : $w = 0.67\ Cb - 0.15$

8 - Shipbuilding and shipping record : $w = Cp^3/(1 + Cp^3)$

9 - Shiffbau Kalender $w = 0.75\ Cb - 0.24$
10 - Papmelj ($Fr > 0.2$) $w = 0.165\ .\ Cb\ \sqrt{\blacktriangledown^{1/3}}\ H - 0.1\ (Fn - 0.2)$

Thrust Deduction :

Due to propeller operation , a region of negative pressure is created just after the ship causing an additional resistance to the ship , thus the thrust is to be increased .
This action is called (thrust deduction) and is considered as a percentage of thrust .

For normal case $S = R$
by the suction $S = R + S\,t$

$$S = R / (1 - t)$$
$$t = (S - R) / S$$
$$t = 1 - R / S$$

t is the thrust deduction

Some approximate formula for (t) :

1 - For single screw ships : $t = 0.5\ Cp - 0.12$ (Hecksher)

$t = K\,w$ (Schoenherr)

$K = 0.5$ to 0.7 for stream lined rudder .
$K = 0.7 \quad 0.9$ for double plate rudder and square rudder post .
$K = 0.9 \quad 1.05$ for single plate rudder .

2 - Twin screw ships :

$t = 0.5\ Cp - 0.18$ (Heckcher)
$t = 0.25\ w + 0.14$ (Schoenherr) with bossing .
$t = 0.7\ w + 0.06$ (Schoenherr) with strut .

3 - Coastal ships	t	$= 0.67\ w$
4 - Motor boats	t	$= 0.0$ to 0.03
5 - Bollard pull	t	$= 0.04$ to 0.05
6 - Going a stern	t_{astern}	$= 1.25\ t$
7 - Trawlers	t	$= 0.77\ Cp - 0.3$

After finding Va and t , the hull efficiency η_H can be written in the following form :

$$\eta_H = R\,.\,V / S\,.\,Va$$

$$\eta_H = R\,.\,V\ (1-t) / R\,.\,V\ (1-w)$$

$$\eta_H = (1 - t)/(1 - w)$$

PROPELLERS

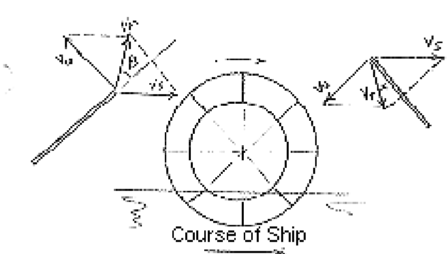
The various propelling mechanisms may be divided into three principal groups :

1 - The JET propulsion which imparts an impulse to the water flowing from ahead and directs it to aft .This type of propeller has the advantage of having practically no parts projecting from the ship's hull and the disadvantage of low efficiency .

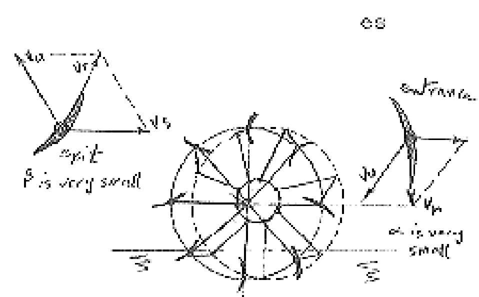
2 - Propellers which derive their thrust in the direction of the ship's course principally from the resisting forces on their moving parts . The paddle wheels are an example .
There are two types of paddle wheels :

(a) Fixed bladed paddle wheel .
(b) Movable bladed paddle wheel .

The perfect action of the wheel depend on the angle between the blades and their resultant speed in respect to the water at their entrance into and exit from the water (α , β) .
For better efficiency , it is recommended that these angles be small so that the entrance and exit of blades take place as smoothly as possible (without shocks) . This problem is solved by using adjustable blades by which the inevitable energy losses are reduced to a minimum due to the smooth entrance and exit of blades into and out of water .
The main disadvantage of paddle wheels is that the high efficiency requires a large diameter and low speed engine which results in a large and heavy engine .It is also noticed that the blades in action are always much less than the actual number of blades of the wheel .



Fixed Bladed Wheel


Movable Bladed Wheel

3 - Propellers which derive their thrust in the direction of the ship's run principally from the lifting forces on their moving parts .

To this group belongs the most important type of propellers which is (The Screw Propeller) .

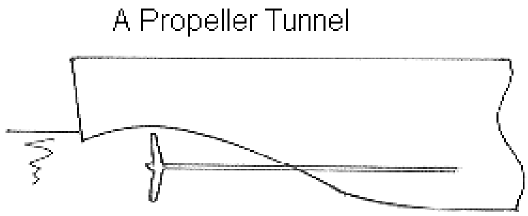
The screw propeller consists of a boss on which from 2 to 7 blades either fixed or movable are mounted .

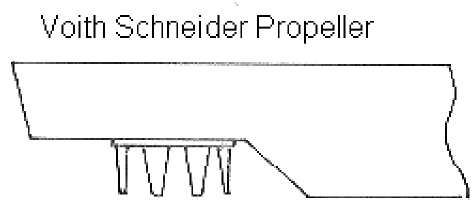
This propeller drives its name from its characteristic movement , namely , the combination of a uniform rotating motion with a uniform progressive movement .

The screw propeller is fitted as low as possible in way of the stern , it should have a diameter such that when the ship is under any loading condition the propeller is sufficiently submerged so that the air drawing is avoided during pitching as possible .

In preliminary design stages the propeller diameter is taken equal to 0.6 to 0.7 T (where T is the draft) .

For some types of inland ships the screw diameter becomes too large relative to the water draft , in such case the propeller is enclosed in a tunnel in which it will be covered by the water .





In contrast to the screw propeller , there is another type which is the vertical axis propeller or (Voith Schneider) propeller .

This propeller is differing from screw propeller and can be classed a nonstationary propeller , it has a large disc fitted in a flat portion of ship's bottom aft , this carries a number of vertical blades acting in such a manner that when the disc rotates a total thrust will act in one direction .

The resulted thrust can be altered by changing the disposition of blades allowing the ship to go a straight ahead, astern or sideways .

this propeller can be used where high maneuverability and restricted drafts are required . Its disadvantages are :

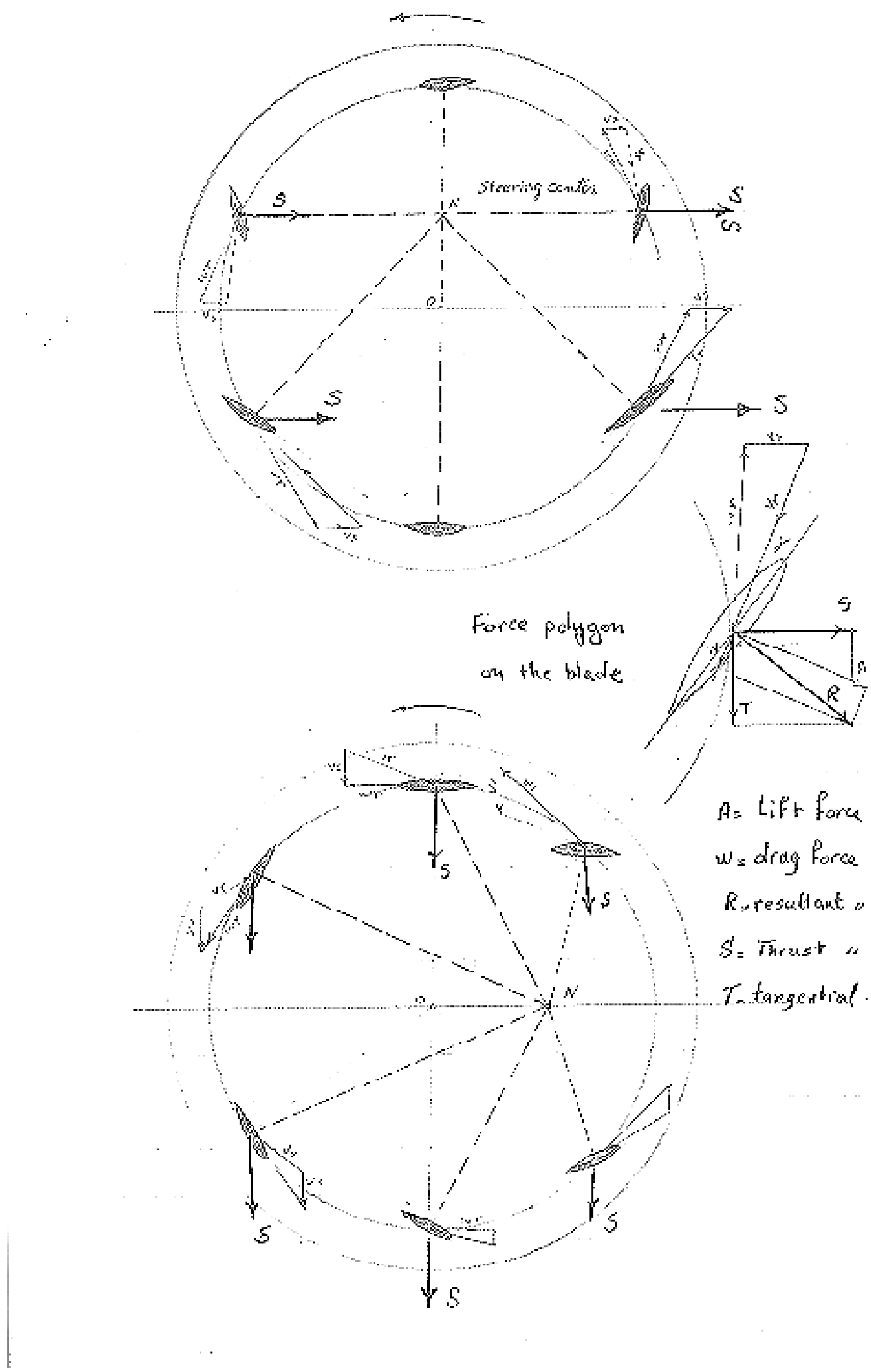
1 - Complicated structure and mechanism .
2 - Low efficiency relative to screw propeller .

The Voith Schneider propeller has rendered good service in practice , there are already a large number of ships and ferries equipped with it , particularly those navigation in rivers , lakes or canals .

The forces acting on the blades can be divided into :

1 - A component acting in the direction of motion of vessel , these components integrated over the circumference results in thrust (S) .
2 - A component at right angles to the direction of motion , these components integrated over the circumference give the value zero .

The thrust is always acting in a line perpendicular to O N .


Steering centre
S
Force polygon
on the blade
A= Lift force
W= drag force
R= resultant "
S= Thrust "
T= tangential "
N
R
T

THE SCREW PROPELLER

The screw propeller forms the basic element of several arrangements which are applied in propelling the ships :

1 - Arrangements concerning the number of propellers :
   (a) Single screw .
   (b) Twin   screw or multiple screw .

2 - Arrangements concerning the pitch of propeller blades :
   (a) Fixed pitch or conventional propeller .
   (b) Controllable pitch propeller .

3 - Arrangements concerning special ideas for improving efficiency :
   (a) Nozzle propellers (decelerating , accelerating) .
   (b) Tandem propellers and contrarotating propellers .
   (c) Overlapping propellers .

Each type of these arrangements is applied for a particular purpose .

<u>Geometry of screw propellers :</u>

When we stand behind the ship looking forward, the surface of propeller blade which is seen is the face or high pressure side ,the opposite surface is called the back or low pressure side of the blade .

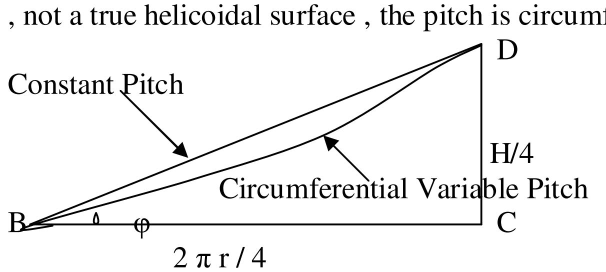
The face of blade is a true helicoidal surface which can be defined as the surface formed by a straight line rotating at a constant velocity around an axis through one of its ends and in the same time moving along this axis by a uniform velocity .
The axial distance covered by one rotation is called the pitch .
If all blade elements reach the same height by one rotation the blade will be called a constant pitch .

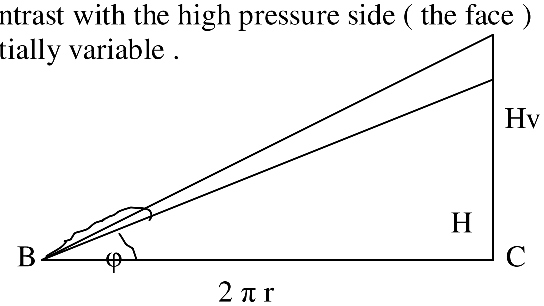
The pitch may vary between blade elements , the blade will be called variable pitch blade .

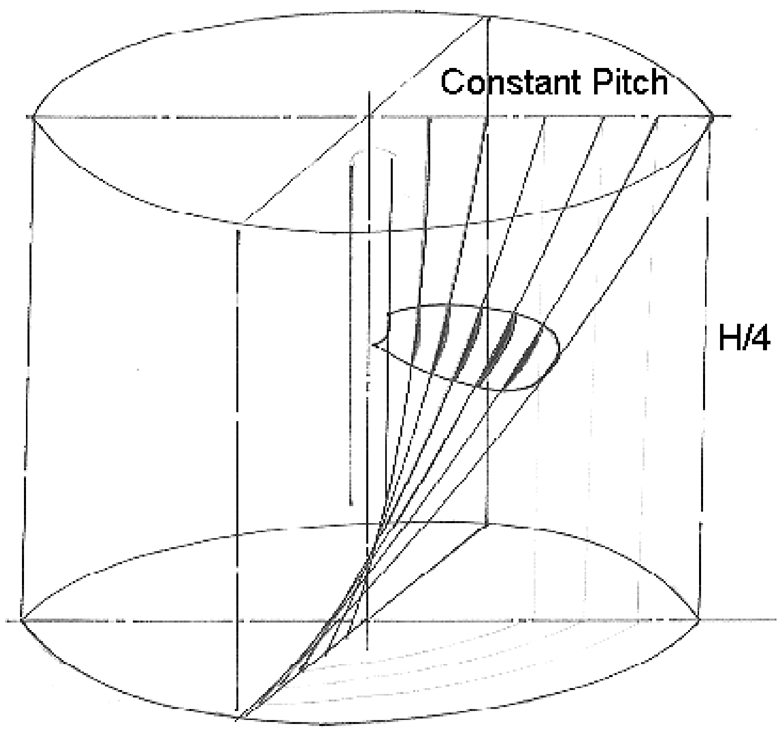
If the areas BCD and B'C'D' and all other similar areas are developed into a flat surface the lines BD , B'D' . . . etc ,always appear to be straight if the helicoidal surface of the propeller blade has a constant or radially variable pitch .

If the face is curved the BD and B'D' ... etc will not be straight lines , they will be curved lines , which means that the blade has a circumferential variable pitch .

The low pressure side of the screw (the back) is in contrast with the high pressure side (the face) , not a true helicoidal surface , the pitch is circumferentially variable .







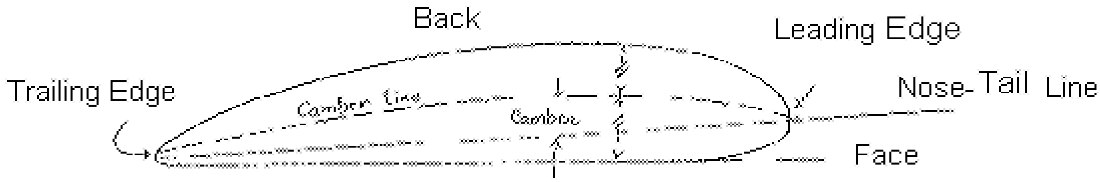
The actual pitch or virtual pitch (Hv) is the mean pitch of the high pressure and low pressure sides

The face pitch is also called nominal pitch is the commonly used pitch in propeller problems because of the following :

(a) It is independent on the shape of blade .
(b) It facilitates the drawing and construction of screw .

The pitch is always given relative to the diameter (H / D) .

Geometry of blade element :



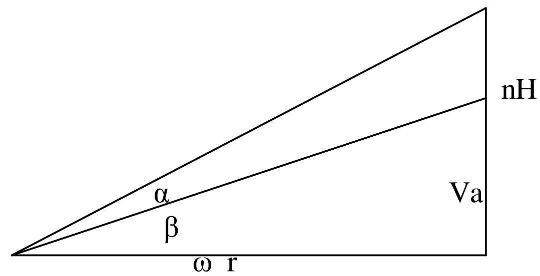
Slip of propellers :

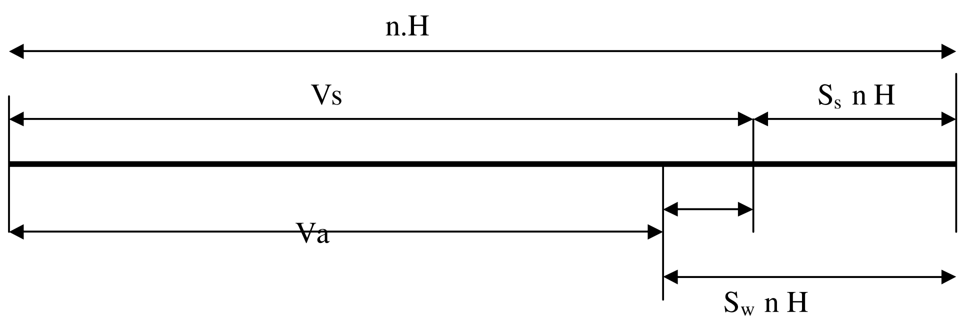
The forward motion of propeller can be considered as a screw , the distance moved after one revolution is the pitch .

However , because the water is accelerated after the propeller the actual distance becomes less than the pitch , the difference is the measure of ship .

Where ;

Slip Velocity = n.H - Va
n r.p.m
H pitch
Va speed of advance .





True slip $S_w = (n.H - Va) / (n.H) = 1 - Va / n.H$

If the speed of advance not known , the slip is often based on ship's speed , and called apparent slip .

$$Ss = (n.H - Vs) / n.H = 1 - Vs / n.H$$

$$(1 - S_w) / (1 - Ss) = Va / Vs = 1 - w$$

w = wake fraction

DRAWING OF SCREW PROPELLER

The drawing of screw propeller are made using various projections , the projections are containing the following :

1 - EXPANDED BLADE AREA :

Is the area of blade expanded on a flat plane by expanding all curved blade elements , it gives the actual area of blade .

2 - DEVELOPED BLADE AREA :

Is the area obtained by rotating each blade element into the plan of drawing . (2 dim.)

3 - PROJECTED AREA :

Is the projection of the screw blade while it is shaped in 3 dimensional form .

4 - THE 3 rd PROJECTION :

Is the side view of blade fitted on the boss , it also shows the maximum thickness distribution along the blade .

The disc area (Ao) is equals to ($\pi D^2/4$), where (D) is the diameter of propeller .

The characteristics of propeller are given in a form of non-dimensional quantities :

Pitch ratio H / D = pitch / diameter

Expanded area ratio (Ae/Ao) or (Fa/F)= expanded area / disc area

Blade thickness fraction = to / D

to = max. blade thickness at shaft axis .

D = Diameter of propeller .

Drawing Steps of Propellers :

1. Begin the drawing with the expanded area.
   a. Draw a generator line,
   b. Draw the lines r= 0.2R , 0.3R , 0.4R , 0.5R ,...., R ,
   c. Draw the blade element profiles according to the offsets given in the tables,
   d. The offsets of the element's thicknesses are given in as a function of the maximum thickness of the blade element ,
   e. The chord lengths of profile are given as percentage of maximum length of the profile at 0.6R
   f. The maximum chord length (at 0.6R) is given as a function of diameter and blade area ratio,
   g. Draw the outline of expanded area .

2. Determine the point F so that AF= $H/2\pi$.

3. Draw straight lines from the point F to the intersections of generator line and the base line (face) of profiles .

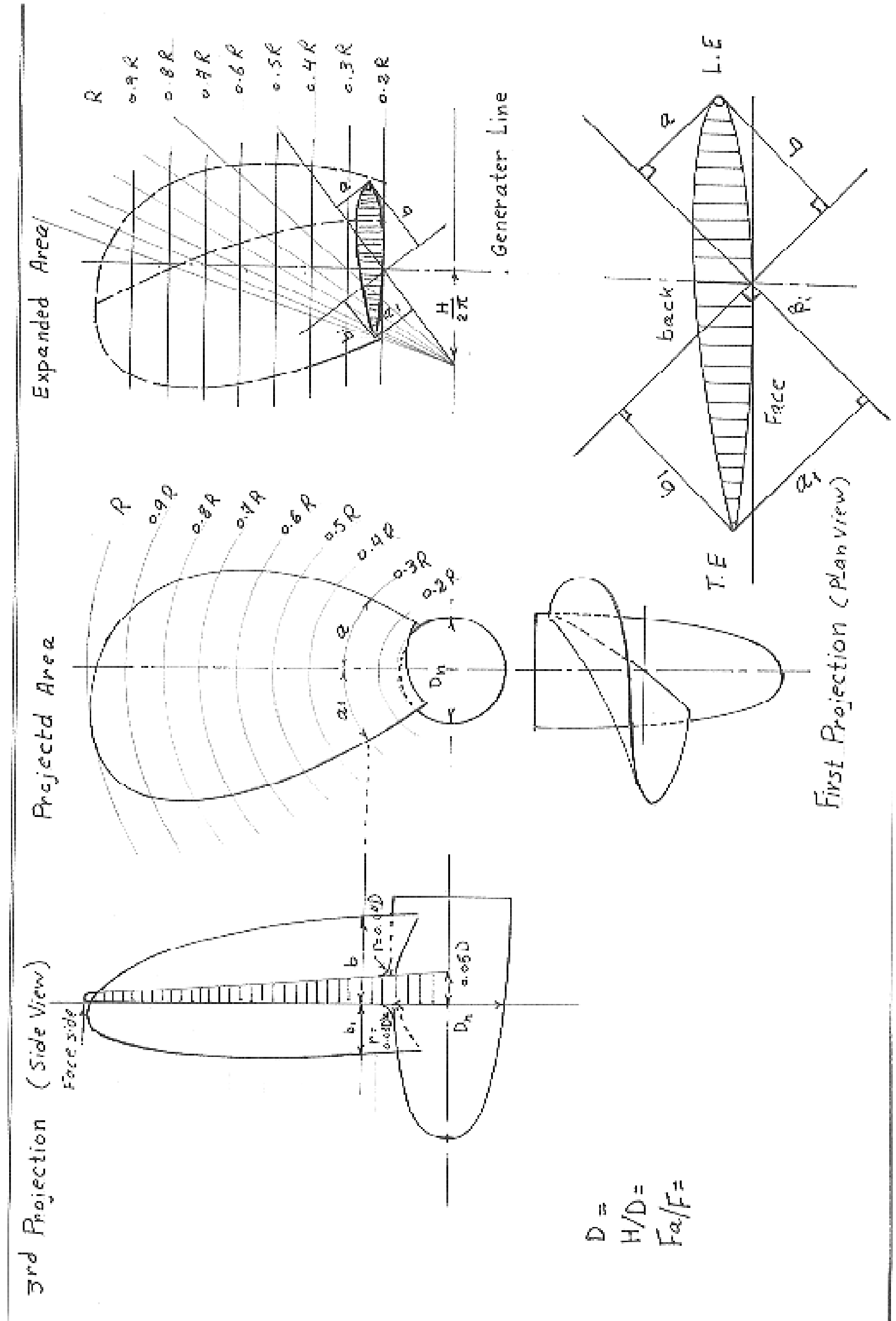
4. Draw perpendicular lines to the lines from (3) at the points of intersections .

5. Draw the parallel lines from the nose and tail to the lines of (3) , (4) and find the distances a , b , a_1 , b_1 as shown in the figure .

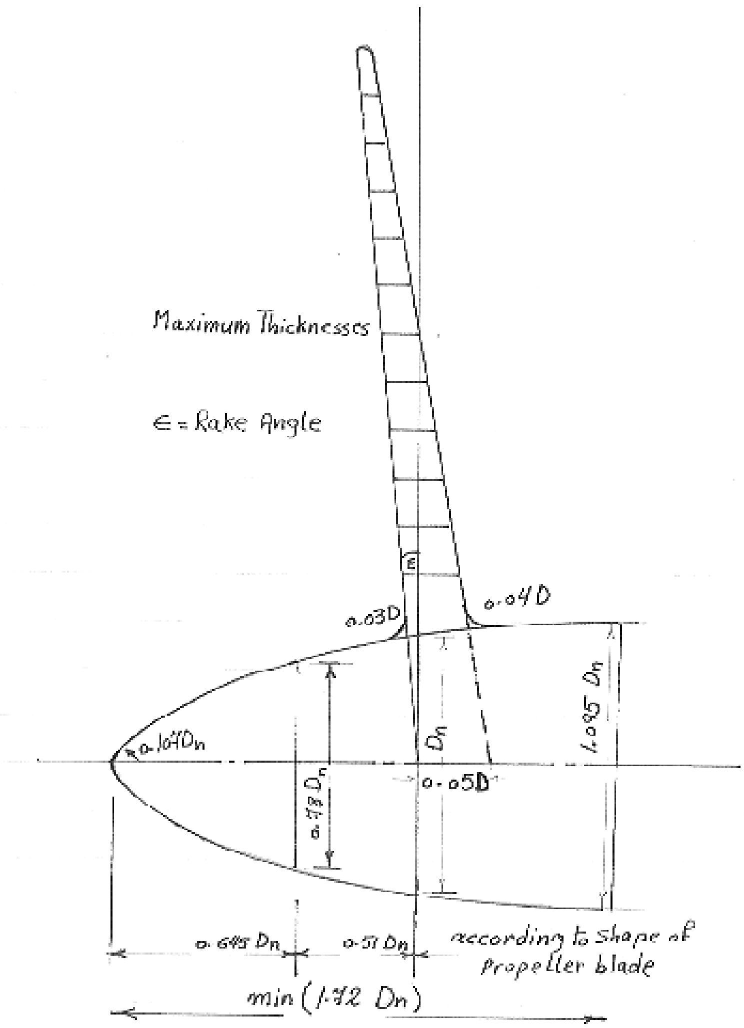
6. Draw the second projection by developing a , a_1 along the corresponding radius .

7. Draw the third projection by adjusting b , b_1 with a , a_1 intersections with the outline of projected area from the second projection after drawing the maximum thickness strip.,

8. The first projection (plan view) could be drawn to make the necessary fairing of the drawings .



3rd Projection (Side View)
Face side
Projectd Area
Expanded Area
Generater Line
First Projection (Plan View)
T.E
L.E
back
Face
R
0.9R
0.8R
0.7R
0.6R
0.5R
0.4R
0.3R
0.2R
D_h
$\frac{H}{2\pi}$
D =
H/D =
Fa/F =



Typical Layout of A Propeller Boss

The Design Features of Marine Screw Propellers

A- The main considerations in choosing and designing screw propellers are :

1. Highest efficiency
2. Minimum risk of cavitation
3. Minimum exciting forces causing vibrations
4. Adequate strength
5. Minimum vulnerability of appendages
6. Reasonable first cost and maintenance cost .

B- Materials of propellers :

a. Cast Iron
b. Cast Steel
c. Manganese Bronze
d. Manganese - Nickel - Aluminum Alloys
e. Bronze - Brass alloys

The manganese bronzes and alloys make tough blades , resistant to erosion and maintain higher efficiency . The cast iron is cheap but has very low tensile strength so that it must be thicker , it also corrodes badly in salt water and less resistant to cavitation .

C- Arrangement of Propeller Blades :

The blades are either integrated with the hub by casting (solid) or casted separately and bolted to the boss (built up) , the advantage of built up propellers is the easiness of replacing blades in case of damage , but the disadvantages are the higher initial costs and less efficiency due to larger hub diameter .

D- Propeller Diameter:

The propeller diameter is a significant element for the efficiency of propeller , it is now widely known that the larger the diameter of propeller the higher the efficiency .

E- The Boss Diameter :

The diameter of boss ranges from 0.15D to 0.25D , the hub is usually cylindrical or conically shaped .

F- Pitch of Propeller :

The pitch ratio for propellers range from 0.6 for heavily loaded propellers to 2.0 or more for high speed motor boats .
For normal B-type propellers , the pitch is given constant for all blade elements if the number of blades is 3 or 5 . But for propellers with 4 blade elements , the pitch is made variable up to the blade element 0.5R , the variation is as follows :H/D

r/R	0.2	0.3	0.4	0.5
H/D	80.3%	88.0%	95.2%	100.0%

G- Rake and Skew of Propeller :

The propeller may be given some rake aft , which increases the clearance with the hull and minimizes the periodic forces inducing vibrations .
The blades may be skewed back , that serves in smoothing the impacts of different blade elements with the varying wake field .

H- The Blade Area Ratio :

The blade area ratio varies from 0.35 to 1.0 for normal B-type propellers , it could be higher than 1.0 for high speed small propellers (G-type)

I- Rounding Radii of Blade Elements mm (% of max. thickness[Si])

r/R	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.95
T.E	6.4	6.5	6.6	6.7	6.8	6.9	7.0	11.9	15.70
L.E	According	to	profile	form				11.1	15.70

MODIFIED B - SERIES PROFILES

Ordinates and Thicknesses

Distances of the Ordinates from the Maximum Thickness

	From Max. Thickness to Trailing Edge					From max. Thickness to Leading Edge						
r/R	100%	80%	60%	40%	20%	20%	40%	60%	80%	90%	95%	100%
Ordinates of Back												
0.95	----	44.80	72.00	88.80	97.20	97.20	88.80	72.00	44.80	29.50	21.60	---
0.90	----	45.15	70.00	87.00	97.00	97.00	87.00	70.00	45.15	30.10	22.00	---
0.80	----	40.95	67.80	85.30	96.70	97.00	85.30	68.70	47.25	31.65	22.45	---
0.70	----	39.40	66.90	84.90	96.65	97.60	88.80	72.15	49.00	32.95	23.00	---
0.60	----	40.20	67.15	85.40	96.80	98.10	89.85	73.55	51.65	34.85	25.30	---
0.50	----	43.40	68.40	86.10	96.95	97.00	89.70	76.00	57.45	42.00	32.95	---
0.40	----	47.70	70.25	86.55	97.00	97.50	90.40	78.35	61.60	48.75	40.75	---
0.30	----	50.95	71.60	86.80	96.80	98.15	91.35	80.45	64.85	53.70	46.55	---
0.20	----	53.35	72.65	86.90	96.45	98.15	92.45	82.35	67.45	57.20	50.60	---
Ordinates of Face												
0.60	5.10	---	---	---	---	----	---	----	----	0.50	1.95	10.25
0.50	9.70	1.75	---	---	---	----	---	0.35	1.70	4.45	7.25	17.05
0.40	17.85	6.20	1.50	---	---	----	0.30	1.75	5.90	9.90	13.45	24.35
0.30	25.35	12.20	5.80	1.70	---	0.45	1.30	4.65	10.90	16.25	19.80	31.00
0.20	30.00	18.20	10.90	5.45	1.55	0.45	2.80	7.40	15.50	21.65	25.95	36.75

Note : The percentages of the ordinates are referred to the Maximum Thickness of the corresponding Sections

Blade Contour :

The blade contour is the length of blade section as % of maximum length of the blade at 0.6R .

Blaade Contour

B. 4 , 5 and C.4				B.3			From max. thickness to L.E % of the corresponding blade width
T.E	L.E	Total	r/R	T.E	L.E	Total	
20.14	----	-----	1.00	14.70	----	----	----
43.11	11.35	54.46	0.95	40.14	17.82	57.96	50.0
47.00	25.35	72.55	0.90	45.46	30.31	75.77	50.0
48.35	41.65	90.00	0.80	48.22	44.63	92.85	47.8
46.68	51.40	98.08	0.70	46.97	52.22	99.19	44.2
43.92	56.08	100.00	0.60	44.18	55.82	100.00	38.9
40.78	57.60	98.38	0.50	40.53	56.52	97.05	35.5
37.30	56.32	93.62	0.40	36.62	54.91	91.53	34.9
33.32	52.64	85.96	0.30	32.67	51.24	83.91	35.0
29.18	46.90	76.08	0.20	28.68	46.05	74.73	35.0

Blade Elements Maximum Thicknesses :

Blade length at 0.2R

5 blades = 0.3327 Fa/F . D

4 blades = 0.4195 Fa/F . D

3 blades = 0.5527 Fa/F . D

Blade length at 0.6R

5 blades = 0.4376 Fa/F . D

4 blades = 0.5467 Fa/F . D

3 blades = 0.7396 Fa/F . D

Blade Thicknesses % of D

r/R	Z = 3	Z = 4	Z = 5
0.2	4.06	3.66	3.26
0.3	3.59	3.24	2.89
0.4	3.12	2.82	2.52
0.5	2.65	2.40	2.15
0.6	2.18	1.98	1.78
0.7	1.71	1.56	1.41
0.8	1.24	1.14	1.04
0.9	0.77	0.72	0.67
1.0	0.30	0.30	0.30

THEORETICAL BASES OF PROPELLER ACTION

The Momentum Theory of Propellers :

The momentum principle of propeller means that the propeller derives its thrust by accelerating the fluid in which it works , in other words , the thrust is developed due to changing the momentum of surrounding water by the screw propeller .

Newton's first law is expressed by :

$F = m \cdot dv/dt$ F = Force or thrust
$F \cdot dt = m \cdot dv$ m = Mass of the body

If the time interval is unity ;

$F = m (V2 - V1)$

For conducting this theory , the following assumptions are concerned :

1. The propeller imparts a uniform acceleration to all the fluid passing through it , so that the thrust generated is uniformly distributed over the disc .

2. The flow is frictionless .

3. There is an unlimited inflow into the propeller .

4. The momentum theory gives no indication to the shape of the screw .

Due to propeller action , the thrust force is generated by jumping pressure at the propeller disc from P1 to P2 , and the propeller induced a velocity in axial direction Ca .

Then , the thrust could be :

$S = (P2 - P1) \, Ao$ ....(1)

Or , $S/Ao = P2 - P1$

Applying momentum principles ;

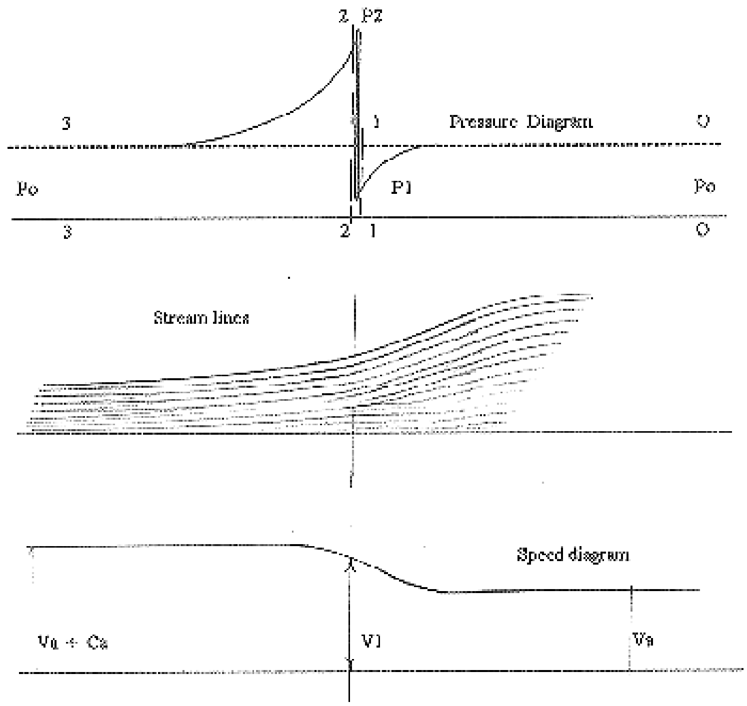
$S = \rho \, Q \, [(Va + Ca) - Va]$ Ca is the axial induced velocity

And $S = \rho \, Ao \, V_1 \, Ca$

V_1 is the velocity of flow through the disc

The thrust per unit area = $\rho \, V_1 \, Ca$ ....(2)

2 P2



Applying B.E. between points O , 1

$$Po + \rho /2\ Va^2 = P1 + \rho/2\ V1^2 \qquad .... (3)$$

Also applying B.E. between points 2 , 3

$$Po + \rho /2\ (Va + Ca)^2 = P2 + \rho /2\ V1^2 \qquad ....(4)$$

Subtracting (4) - (3)

$$P2 - P1 = \rho /2\ [(Va+Ca)^2 - Va^2]$$

$$= Va^2 + 2\ Va\ Ca + Ca^2 - Va^2$$

$$P2 - P1 = \rho /2\ Ca\ (2\ Va + Ca) \qquad ....(5)$$

Thus

$$V1 = Va + Ca /2$$

And $S = \rho\ Ao\ Ca\ (Va + Ca /2)$

That means , the induced velocity at the disc of screw equals to half the total induced velocity . This is the first result of applying momentum theory on propeller action .

Determination of Ideal Efficiency of Propeller Using Momentum Theory .

Output Power of Propeller = $S\ .\ Va\ /\ 1000$

Absorbed Power of propeller = S . V1 / 1000

$$\eta_{pi} = Va / (Va + Ca /2)$$

$$Csi = S / 0.5 \rho \ Ao \ Va^2 = \rho \ Ao \ Ca (Va + Ca /2) / 0.5 \rho \ Ao \ Va^2$$

$$Csi = 2 \ Ca (Va + Ca/2) / Va^2$$

$$= 2 [Ca / Va] [1 + Ca / 2 \ Va]$$

Csi is the thrust loading coefficient which gives an idea about screw loading .

$$4 / \eta_{pi} = 1 + Ca / 2 \ Va$$

$$Csi = 4 (1 / \eta_{pi} - 1) (1 / \eta_{pi})$$

$$= 4 (1 /\eta_{pi}^2 - 1 / \eta_{pi}) = 4 (1 - \eta_{pi}) / \eta_{pi}^2$$

Adding unity to each side of the equation :

$$1 + Csi = 4 (1 - \eta_{pi}) / \eta_{pi}^2 + (\eta \ pi / \eta_{pi})^2$$

$$= (4 - 4 \eta_{pi} + \eta_{pi}^2) / \eta_{pi} = (2 - \eta_{pi})^2 / \eta_{pi}^2$$

$$\sqrt{1 + Csi} = (2 - \eta_{pi}) / \eta_{pi} = (2 /\eta_{pi}) - 1$$

$$2 / \eta_{pi} = 1 + \sqrt{1 + Csi}$$

$$\eta_{pi} = \frac{2}{1 + \sqrt{1 + Csi}}$$

This equation shows that the lower the screw loading the higher the efficiency , and also the ideal efficiency of 100% is given at Csi = 0.0

2. Application of Momentum Theory in circumferential direction:

The blade is divided into sections as shown :

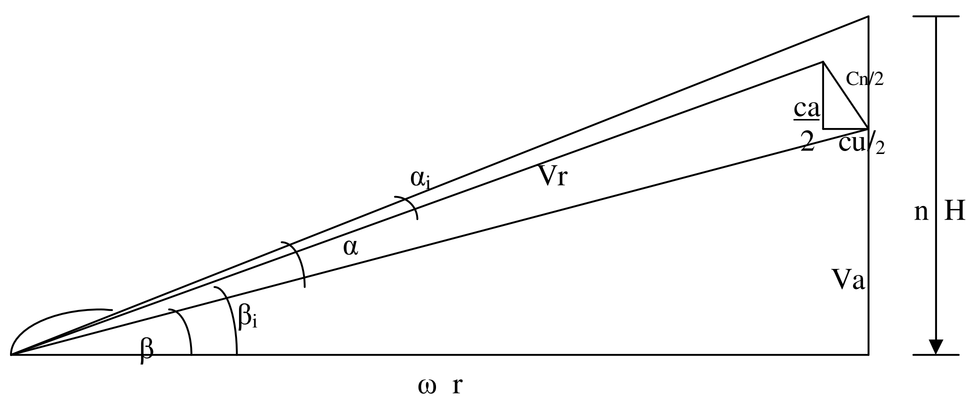
$dQ = V1 \,.\, dA \quad = (\, Va + Ca/2 \,)\, dA$

Tangential Force $dF_t = \rho\, dQ\, Cu$

$$\eta_{bi} = \frac{d_S\, Va}{d_F\ \omega\ r} = \frac{\rho\ dQ\, Ca\, Va}{\rho\ dQ\, Cu\ \omega\ r}$$

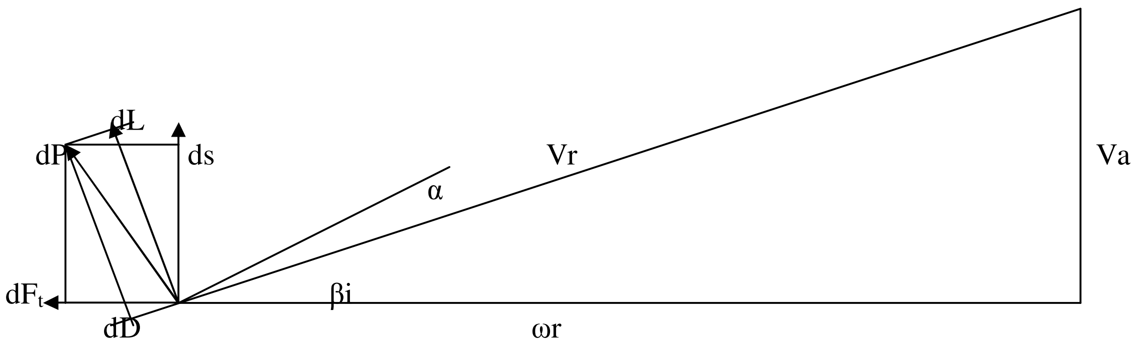
$$\eta_{bi} = \frac{Ca\ Va}{Cu\ \omega\ r}$$

Where η_{bi} is the blade element efficiency .



It is possible to investigate the influence of rotation in the screw race on propulsive efficiency . For a rotating movement , a momentum equation can be also derived . For the blade element shown at radius r with an area dA and rotating at a uniform angular speed ω , the tangential force is dF_t and the torque is $dF_t\ .r$.

Cu/2 = Circumferential component of induced velocity
Ca/2 = Axial Component of induced velocity
Cn/2 = Resultant (Normal) induced velocity
β = Hydrodynamic pitch angle
β_i = Hydrodynamic pitch angle corrected for induced velocities
α = Angle of attack
α_i = Angle of attack corrected for induced velocities



From the velocity diagram it is evident that :

$$\frac{Ca}{Cu} = \frac{\omega\ r - Cu/2}{Va + Ca/2}$$

$$\eta_{bi} = \left(\frac{Va}{Va + Ca/2}\right)\left(\frac{\omega\ r - Cu/2}{\omega\ r}\right) = \eta_{pi}\ \frac{\omega\ r - Cu/2}{\omega\ r}$$

3. Blade Element Theory of Screw Propellers.

According to this theory the screw blade is divided into a number of elements , for each blade element the forces which are set up are calculated, these forces are dependent on the magnitude of the relative velocity Vr , the angle of attack α , and the area of blade element .

On the blade element , a lifting force dL is setup perpendicular to the direction of Vr and a drag force dD acts in the direction of Vr

The components dL & dD combined , yield a force dP , which resolved in the direction of translation and a direction perpendicular to it yield the components of thrust dS and torque dTq .

$$S = Z \int_0^R dS = Z \int_0^R (dL \cos \beta_i - dD \sin \beta_i)$$

$$Tq = Z \int_0^R dF_t\ r = Z \int_0^R (dL \sin \beta_i + dD \cos \beta_i)\ r$$

S = Thrust for Z blades
Z = Number of blades of propeller
dF_t = Tangential force of blade element
Tq = Torque for Z blades

$$\eta = \frac{\int_0^R (dL \cos \beta_i - dD \sin \beta_i)\ Va}{\int_0^R (dL \sin \beta_i - dD \cos \beta_i)\ \omega\ r}$$

Lift - Drag Relationship for Aerofoil Section in Real Conditions

In viscous fluids an aerofoil of infinite span has a profile resistance consisting of frictional and pressure components .

For finite span conditions , an induced resistance is added to the former components .

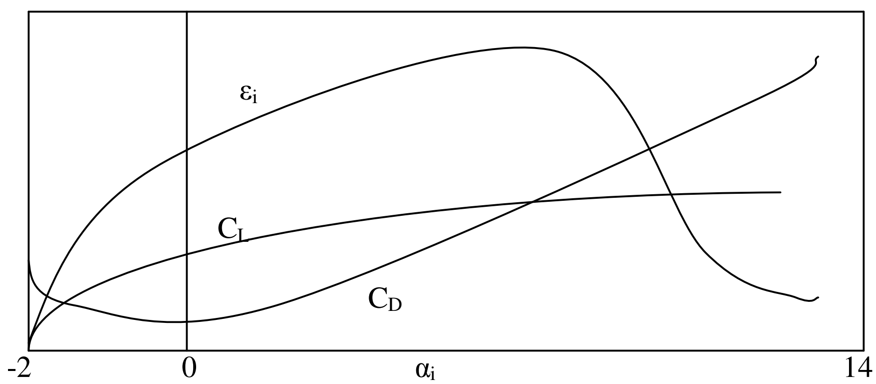
The lift and drag forces relationship give a representative notation about the quality of an aerofoil .

$C_L = L / 0.5\ \rho\ A_o\ V^2$

$C_D = D / 0.5\ \rho\ A_o\ V^2$

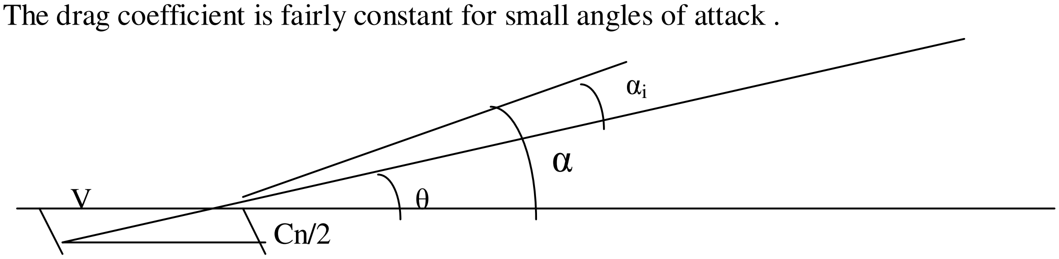
D = Profile resistance + induced resistance

Lift - Drag ratio = $\varepsilon_i = C_L / C_D$



From the figure the following is observed :

1. For small angles of attack the lift coefficient C_L is directly proportional to α_i.
2. The angle α_i at which the lift L = 0.0 is not zero but negative , the magnitude of this angle is dependent on the shape of aerofoil .
3. The drag coefficient is fairly constant for small angles of attack .



Relation between effective and geometrical angles of attack

MODEL TESTS AND LAWS OF COMPARISON FOR PROPELLERS

In research experiments it is necessary to investigate propeller characteristics by means of model tests .
The laws of comparison applied in ship resistance are still applicable .

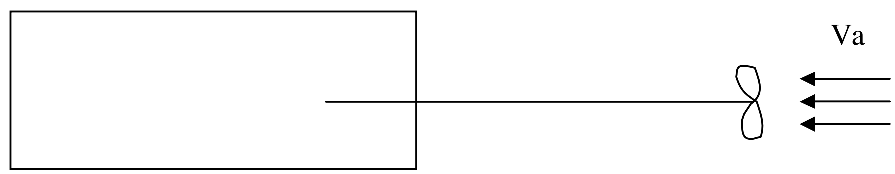
For conducting these model experiments the following four principal types of model tests are distinguished .

a. The Open Water Screw Test
b. The Model Self-Propulsion Test (ship model + screw at different speeds)
c. The Over Load test (ship model + screw at constant speed but with different tow rope forces).
d. The Screw Test in Cavitation Tunnel .

A- The Open Water Test of Screw

The open water screw tests are carried out with the aid of propeller dynamometer for measuring torque and thrust placed in a fine wooden boat . The propeller is placed in front of the wooden boat in the homogeneous velocity field .

The Similarity can be fulfilled by satisfying the following :



1. Geometrical Similarity : In which the propeller is produced in a reduced scale .
2. Kinematic Similarity : In which the ratio between 2 velocity fields in the model and actual propeller is to be constant .

$$(Va/ \pi n d)_m = (Va / \pi n d)_p = \lambda$$

$\lambda_m = \lambda_p$ is necessary to satisfy kinematical similarity .

$s_w = 1 – Va / n.H$ $\quad$ $Va / n.H = (1 - s_w)$

$\lambda = (1 - s_w) H / D$

The kinematical similarity means also the similarity of slip .

3. Dynamical Similarity :

For dynamical similarity Froude's and Reynolds' laws of comparison may be concerned :

- Froude's number for screw is defined as follows :

$F_n = \pi n D / \sqrt{g D} = \pi n \sqrt{D/g}$ D = Propeller diameter.

For similitude , the value of Fr for model must be equal to that of the prototype .

$$Fn_m = Fn_p$$

$$(\pi \; n \sqrt{D/g})_m = (\pi \; n \sqrt{D/g})_p$$

$$n_m \sqrt{D_m/D_p} = n_p$$

$$n_m = n_p \sqrt{\alpha_L} \qquad \alpha_L = D_p / D_m$$

- Also Reynolds' number must be the same for model and prototype .

$$Rn = C \; L_{0.7} \; n \; D / \nu$$

$$C = [\lambda^2 + (0.7 \pi)^2]^{0.5}$$

$$V = \sqrt{(\pi \; n \; 0.7 D)^2 + Va^2}$$

$$= n D \sqrt{(0.7 \; \pi)^2 + (Va/nD)^2}$$

$$(L_{0.7} \; n \; D / \nu)_m = (L_{0.7} \; n \; D / \nu)_p$$

$L_{0.7}$ is the length of profile at 0.7 R .

For the same kinematic viscosity (ν)

$$n_m / n_p = (L_{0.7\,p} / L_{0.7\,p})(D_p / D_m)$$

So $n_m = n_p \; \alpha_L^2$

This means that it is impossible to satisfy Froude's and Reynolds' laws at the same time . But as the open water tests are carried out while the propeller is fully submerged , it follows that Froude's law can be left out of account .

Calculation of Thrust and Torque Coefficients

From Newton Law of comparison :

$$S = C_s \ \rho U^2 \ A / 2 \qquad U = \pi D n \quad , \quad A = \pi D^2 / 4 = \text{Disc area}$$

$$C_s = S / 0.5 \ \rho (\pi D n)^2 \ \ \pi D^2 /4$$

$$C_s = (8/\pi^3) (S / \rho n^2 D^4)$$

The thrust coefficient for propeller could be as follows :

$$K_s = S / \rho n^2 \ D^4$$

Also the torque coefficient could be determined in the same way :

$$M = C_m \ 0.5 \ \rho U^2 \ A \ D / 2$$

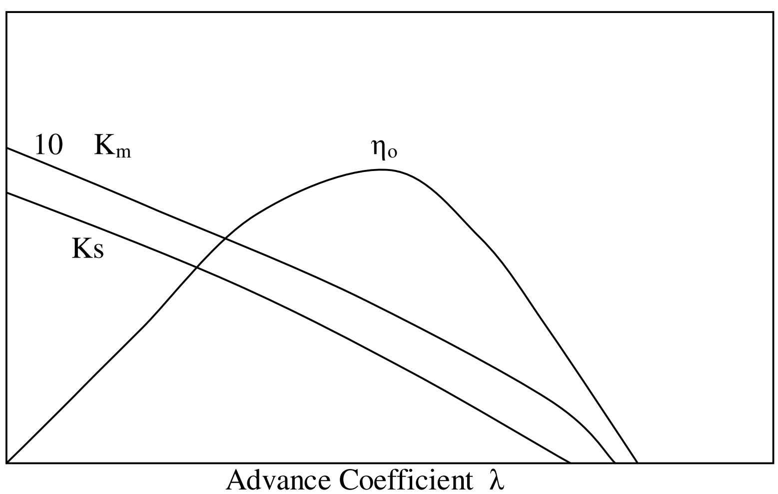
$$C_m = (16/ \pi^3) (M / \rho n^2 \ D^5)$$

$$K_m = M / \rho n^2 \ D^5$$

And as $\eta_o = S.Va / M \omega$

Then $\eta_o = (K_s / K_m) (\lambda / 2 \pi)$

By measuring S, M , n , Va , and calculating K_m , K_s , η_o , λ , and s_w the open water diagrams are arranged .
The Reynolds's number for open water tests is taken 2×10^6 , if for practical applications Rn differs than this value , a correction has to be made .



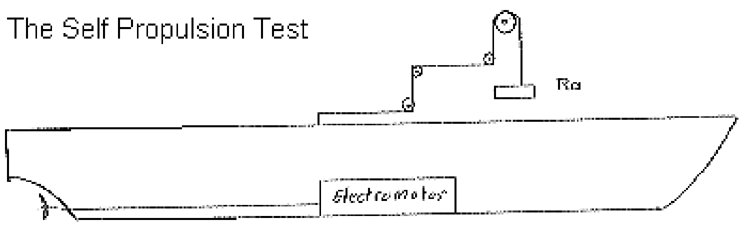
Open water diagram for propellers

B. The Model Self Propulsion Test of Propeller .

Best model in respect of resistance and best open water screw don't give the best combination .
Due to this fact , the self propulsion tests are performed using ship model and propeller model fitted with electromotor for propulsion of the tested configuration .
In this condition , there is no deviation from Froude's law .

$$n_m = n_p \sqrt{\alpha_L}$$

The ship model is propelled by its own screw which has a constant number of revolutions during a measuring run .
The towing carriage keeps running over the model at the same speed , then the thrust S , Torque M , number of revolutions n and V are measured .
The self propulsion tests are generally consist in carrying out a number of measuring runs within a specified speed range during which for each speed a corresponding tow rope force Ra is acting in the direction of motion and provided to compensate for the relative difference in frictional resistance between model and ship .



$$R_{tm} = R_{fm} + R_{rm}$$

$$R_{ts} = R_{fs} + R_{rs} \qquad \text{Dividing by } \alpha_L^3$$

$$Rts / \alpha_L^3 = R_{fs} / \alpha_L^3 + R_{rs} / \alpha_L^3 \qquad\qquad R_{rs} / \alpha_L^3 = R_{rm}$$

$$R_{tm} - R_{ts} / \alpha_L^3 = R_{fm} - R_{fs} / \alpha_L^3 = Ra$$

$$(R_{fm} - Ra) \ \alpha_L^3 = R_{fs}$$

$$Ra = R_{fm} - (R_{fs} / \alpha_L^3)$$

$$Ra = (C_{fm} - C_{fs}) \ \rho / 2 \ V_m^2 \ Ws_m$$

Ra = The friction correction
R_{fm} = Frictional resistance of model
R_{fs} = Frictional resistance of ship,
Ws_m = Wetted surface of model

The values of torque , thrust , number of revolutions , and speed can be determined for the actual ship using the scale factors as follows :

M_m (Torque) x α_L^4 = (Torque $)_s$
S_m (Thrust) x α_L^3 = (Thrust $)_s$
n_m (Rps) / $\sqrt{\alpha_L}$ = (Rps $)_s$
Va (Speed) x $\sqrt{\alpha_L}$ = (Speed $)_s$

C. The Overload Test of Propellers .

In contrast to normal self propulsion test with various speeds , In overload test the screw loading is varied by varying the towing force Ra' .
The model is moved at a constant speed and the friction correction Ra is systematically altered , that is to determine the effects of changing propeller loading on the performance of the tested configuration .
The condition in which the towing force equals to the friction correction of that speed is called the self propulsion point of ship or tank condition . While the condition in which the Ra'= 0.0 is termed as self propulsion point of the model and in the same time an overload point of the actual ship .
This method in carrying out the self propulsion test has the advantage that accurate values are obtained for the effects of the overloading of propellers on screw efficiency and number of revolutions .
The best way of experimental investigation of ship propulsion in the model basin is to supplement a self propulsion test within a specified speed range by an overload test at the trial or service speed .

D. Screw Test in Cavitation Tunnel .

For making predictions in the design of screws about the occurrence of cavitation and screw behavior under cavitating conditions , a model test in the cavitation tunnel is required .
The cavitation charts which are produced from such experiments are of large help to propeller designers who can determine the necessary blade area for developing the required thrust at the maximum possible efficiency and cavitation-free conditions . .

Example :
For conducting the self propulsion test for a ship , a model of scale factor 22.5 is used . The following results are recorded from the model test .

V_m = 1.4594 m/s
n_m = 7.00 rps
S_m = 2.15 Kp,
M_m = 7.89 Kp.cm
D_m = 0.25 m
And the test is done in fresh water .
The propeller model has the following open water results at n = 9.0 rps

Va m/s	M_m	S_m
1.24	14.70	4.125
1.35	13.02	3.470
1.42	11.95	3.050
1.50	10.72	2.560
1.58	9.50	2.080

The total resistance of model - reduced by Ra - at speed of 1.4594 m/s is 1.732 Kp .

Calculate the wake fraction w , thrust deduction t , and for the actual ship calculate P_D , n_s , η_o , η_B , η_D , η_p , $\eta_{o.a}$ taking into account that the ship operates in salt water , and taking the gearing and mechanical losses of 0.04 .

Solution :
The wake fraction may be determined on the basis of equal K_m for model during test and from open water results .

Ve	λ	K_s	K_m	η_o
1.24	0.5510	0.12790	0.01823	0.615
1.35	0.6000	0.10755	0.01615	0.636
1.42	0.6310	0.09455	0.01481	0.641
1.50	0.6665	0.07935	0.01329	0.633
1.58	0.7020	0.06447	0.01177	0.612

$\lambda = Ve / n D$
$Ks = S / \rho n^2 D^4$
$K_m = M / \rho n^2 D^5$

$\eta_o = (K_s / K_m) . (\lambda / 2\pi)$

Then , the open water diagram could be drawn .
From the experiment at 7 rps ,

$Km = 7.89 / (102 \times 7^2 \times 0.25^5) = 0.01615$

From the table or the open water diagram the corresponding $\lambda = 0.60$

$Va = \lambda D n = 0.60 \times 7 \times 0.25 = 1.050$ m/sec

$w = 1 - Ve / Vs = 0.28$

$t 0 = 1 - R / S = 1 - 1.732 / 2.15 = 0.194$

P_D (ship) = P_D (model) x $\alpha_L^{3.5}$

P_D (model) = M_m x 2 $2\pi n / 75$ H.P.
3.5
P_D (ship) = P_D (model) $\alpha_L^{3.5}$ $(\gamma_{sw}/\gamma_{fw})$

$= (0.0789 \times 7 \times 2\pi \times 22.5^{3.5} \times 1025/1000) / 75$
= 2560.0 H.P.
P_T (ship) = P_T (model) x $\alpha_L^{3.5}$
P_T (model) = S_m x Va_m / 75

P_T (ship) $= 2.15 \times 1.05 \times 22.5^{3.5} \times 1.025 / 75 = 1667$ H.P.

$\eta_B = P_T / P_D = 1667 / 2560 = 0.651$
0 η_o from the diagram at $\lambda = 0.60$

$\eta_o = 0.636$, $\eta_R = \eta_B / \eta_o = 1.024$

$\eta_D = P_E / P_D$

$P_E = [R . V / 75] \alpha_L^{3.5} (\gamma_{sw}/\gamma_{fw})$

$P_E = 1.732 \times 1.4594 / 75 \quad (1.025) \; 22.5^{3.5}$

$\eta_D = 1866 / 2560 = 0.729$

$\eta_p = P_E / P_S = 1866 / 2560 \times 0.98$ (taking 2% transmission losses)

$\eta_p = 0.714$

$\eta_{o.a} = P_E / P_B$

$P_B = P_S / 0.96 = 2560 / 0.98 \times 0.96 = 2721$ H.P

$\eta_{o.a} = 1866 / 2721 = 0.6858$

$n_s = n_m / \alpha_L^{0.5} = 7 / 22.5^{0.5} = 1.4757$ rps

THE DESIGN OF PROPELLERS

The design of propellers is performed in two main ways :

1. Using systematic series
2. Using circulation theory (Lifting line & lifting surface theories)

The Design of Propellers with the Aid of Systematic Series Diagrams .

An important method of screw design which is based on the results of open - water tests on systematically varied series of screw models . These series comprise models whose characteristic screw dimensions such as pitch ratio H/D , number of blades Z , shape of blade section , and blade thickness are systematically varied .
There are many series to be found , we will deal with Wageningen B - Type propellers of N.S.M.B .

The design charts of B - type propellers are made for different number of blades and different blade area ratios as follows :

Z	2	3	4	5
	B2.3	B3.35	B4.40	B5.45
		B3.50	B4.55	B5.60
		B3.65	B4.70	
dn/D		0.18	0.167	0.167

Design Details of B - Screw Propellers

The B- type propeller is constructed from airfoil shaped sections up to 0.6R followed by circular back profiles .

Rounding off Radii for Edges :

All profiles have rounding off radius at leading edge and trailing edge , they are often given in offsets table , otherwise use the following values :
Rounding off radii at boss R (face) = 0.03 D R1(back) = 0.04 D
At 0.95 R :

0.001 D (T.E.) & 0.002 D (L.E.) for bronze brass propellers but not to be less than 3 ~ 4 mm
0.0015 D (T.E.) & 0.003 D (L.E.) for grey cast iron , cast steel but not less than 5 ~ 6 mm
.

Using B - series Diagrams for Propeller Design :

The open water series of propellers are available in the form of charts for propeller design , the forms of open water charts are as follows :

1 - Bp - δ diagrams for marine engineering approach
2 - Bu - δ diagrams for naval architecture approach

This group of charts are the original charts given by N.S.M.B .

In Rostok university , they developed the propeller design charts in a simpler form to be handled by the designer , they produced another group of charts as follows :

1 - S - λ diagrams for naval architecture approach
2 - Nw - λ diagrams for marine engineering approach .

The S - λ diagrams and Nw - λ diagrams :

These diagrams use non-dimensional factors to determine the optimum efficiency , pitch ratio , and other design characteristics of the propeller at a given condition of thrust , Ve , D , or n .

$$Td = \frac{1}{D.Ve}\sqrt{\frac{S}{\rho}} \quad , \quad Tn = \frac{n}{Ve^{2}}\sqrt{\frac{S}{\rho}}$$

$$Td = \sqrt{\frac{Ks}{\lambda^{2}}} \quad , \quad Tn = \sqrt{\frac{Ks}{\lambda^{4}}}$$

From Td and Tn curves , intersection with ηp maximum , the other characteristics of the propeller could be determined , these characteristics are :

- The pitch ratio H/D
- The advance coefficient λ
- The diameter (D) or number of revolutions (n)
- The efficiency ηp and torque coefficient Km

This approach is called <u>naval architecture approach</u> as it starts the design procedure by the thrust and diameter of the propeller .

The Nw - λ diagrams are the complementary design charts which facilitate the <u>marine engineering approach</u> which starts the design procedure by the developed power P_D and number of revolutions of the propeller .

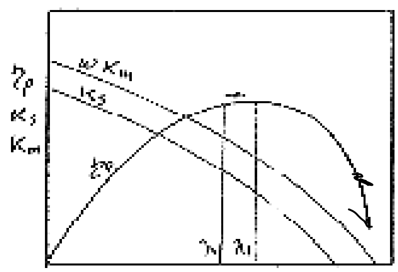
$$Pd = \frac{1}{D.Ve}\sqrt{\frac{Nw}{2\pi\rho Ve}} = \sqrt{\frac{Km}{\lambda^{3}}}$$

$$Pn = \frac{n}{Ve^{2}}\sqrt{\frac{Nw}{2\pi\rho Ve}} = \sqrt{\frac{Km}{\lambda^{5}}}$$

From intersections of Pd or Pn with the curves of ηp maximum , the design characteristics of the propeller could be obtained , these characteristics are :
- The pitch ratio H/D
- The advance coefficient λ
- The diameter (D) or number of revolutions (n)
- The efficiency ηp and thrust coefficient Ks .

In both diagrams there are 3 curves for maximum efficiency which are corresponding to the non-dimensional factor by which we are going through the design procedure .

It is a common practice to reduce the optimum diameter of propeller which comes out from charts to insure the least loss of efficiency due to ship - model correlation .



The open water charts of propellers are applied not only in design problems , but also in other problems such as the calculation of maximum attainable speed of the ship , performance analyses of an existing propeller , determination of tow rope pull and bollard pull .
In applying the methods given in these charts , for intermediate values of Ks , Km , H/D , and ηp we can use linear interpolation , but for intermediate values of Td , Tn , Pd and Pn a mixed interpolation is applied by using half logarithmic and half linear interpolations .
For example , if the distance between two curves is 10 units and the intermediate point is at the middle , the actual distance would be :

$$\frac{0.50 + \log 5}{2} = 0.6$$

which means that the point will be at 60% of the distance between the two curves .

Examples :

1. Calculate the optimum diameter , the developed power and the efficiency of a screw B3.35 if the following are given :

Ve = 5.59 m/s , n = 1.507 rps , S = 84000 Kp

Solution :

$$Tn = \frac{n}{Ve^{2}}\sqrt{\frac{S}{\rho}} \quad = \quad \frac{1.507}{5.59^{2}}\sqrt{\frac{84000}{104.8}} = 1.365$$

From intersection with ηp max. for Tn constant , λ = 0.504

Reducing D by 6% → λ = 0.534
Again from intersection of new λ with the line of Tn = 1.365

H/D = 0.7858
Km = 0.0198

$$D = \frac{Ve}{n.\lambda} = 5.95 \ / \ 1.507 \text{ x } 0.534 = 6.95 \text{ m}$$

$$Nw = 0.0198 \text{ x } 2\ \pi\ \rho\ n^{2} \cdot D^{5}$$

P_D = Nw / 75 = 9604 H.P.

$$\eta p = \frac{S.Ve}{Nw} = \frac{84000x5.59}{75x9604} = 0.649$$

Example 2.

Calculate the optimum diameter , pitch ratio and efficiency of the B3.50 if the following are given :
Ve = 7.51 m/s n = 3.15 rps Developed power P_D = 4040.0 H.P

Solution :

$$Pn = \frac{n}{Ve^2}\sqrt{\frac{Nw}{2\pi\rho Ve}} =$$

$$Pn = \frac{3.15}{7.51^2}\sqrt{\frac{4040x75}{2x3.14x\rho x7.51}} = 0.4375$$

From intersection with ηp max. for Pn constant , → λ = 0.613 , Ks = 0.115 ,
and H/D = 0.80

$$D\ opt. = \frac{7.51}{3.15 \times 0.613} = 3.89\ m$$

Reducing D by 5% → D = 3.696 → λ = 0.645

Again , intersection of new λ with the line of Pn = 0.4375 ,

H/D = 0.86 , Ks = 0.135

$$S = 0.135 \times \rho \times 3.15^2 \times 3.695^4$$

$$\eta p = \frac{S . Ve}{Nw} = \frac{26196 \times 7.51}{4040 \times 75} = 0.65$$

Example 3 .

A propeller B4.40 to be designed , the diameter is given by the dimension of screw aperture = 5.4 m , the thrust = 28950 Kp , and the speed of advance = 5.45 m/s .
Find , n opt. , H / D , P_D , ηp
Solution :

$$Td = \frac{1}{D.Ve}\sqrt{\frac{S}{\rho}} = \frac{1}{5.4x5.45}\sqrt{\frac{28950}{104.8}} = 0.56$$

From intersection of Td = 0.56 with ηp max. at Td constant →

λ = 0.744 , H/D = 1.025 , Km = 0.0298

$$n\ (optimum) = \frac{5.45}{5.4x0.744} = 1.385\ rps = 81.5\ rpm$$

$Nw = Km\ 2.0\ \pi\ \rho\ n^3 D^5$ = 0.0298 x 2 π x 104.8 x 5.4 ** 5 x 1.385**3

P_D = Nw / 75 = 2993 H.P ηp = S.Ve /Nw = 0.69

Example 4:

The following are given for a B3.50 propeller : Ve = 4.35 m/s D = 1.7 m , P_D = 500 H.P .
Determine : n opt. , H/D , S , ηp

Solution :

$$Pd = \frac{1}{1.7x4.35}\sqrt{\frac{500x75}{2x3.14x104.8x4.35}} = 0.49$$

From intersection of Pd = 0.49 with ηp max. at Pd constant →

λ = 0.434 , H/D = 0.739 , Ks = 0.160

$$n\ opt.\ \frac{4.35}{1.7x0.434} = 5.95\ rps \quad = 354\ rpm$$

$$S = Ks\ \rho\ n^2 D^4 \quad = 0.16x104.8x5.95^2 x1.7^4 = 4875\ \ Kp$$

ηp = S.Ve /Nw = 4875 x 4.35 / (500 x 73) = 0.565

Example 5 :

It is required to determine the maximum attainable speed for a ship having the following B4.40 propeller particulars : D = 1.9 m , P_D = 500 H.P , w = 0.35 .
The S - Ve relationship is given below :

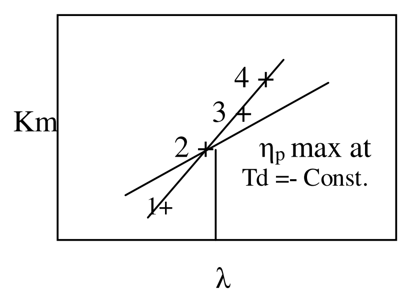
S	6700	5270	4240	3615	Kp
Ve	4.2	4.0	3.84	3.675	m/s

Required : H/D , n , Ve , Vs

Solution :
From S-λ diagram for the given propeller information , the corresponding values for λ , n , Td and Km are determined .

Td	1.002	0.932	0.8715	0.8415	
λ		0.452	0.480	0.494	
n		4.64	4.21	3.915	n = Ve / D λ
Km		0.0231	0.0308	0.0384	Km = P_D x 75 / 2πρ n **3 D**5

Now it is necessary to plot a relation λ - Km which intersects the line of ηp max at Td constant at a point which will be the optimum point .



λ = 0.45 , H/D = 0.7655 , Km = 0.0227

$$n = \sqrt[3]{\frac{500x75}{2x3.14x104.8x24.761x0.0224}} = 4.66rps$$

Ve = λ D n = 3.99 m/s Vs = Ve / (1 - w) = 6.14 m/s

Example 6 :

For an increased resistance condition by fouling of a ship has a B4.40 propeller , it is required to find the relation P_D - Ve , n , ηp . given that D =2.0 m , H/D = 0.75 .
The relation S - Ve is given below :

S	7545	4874	3740
Ve	4.18	3.84	3.51

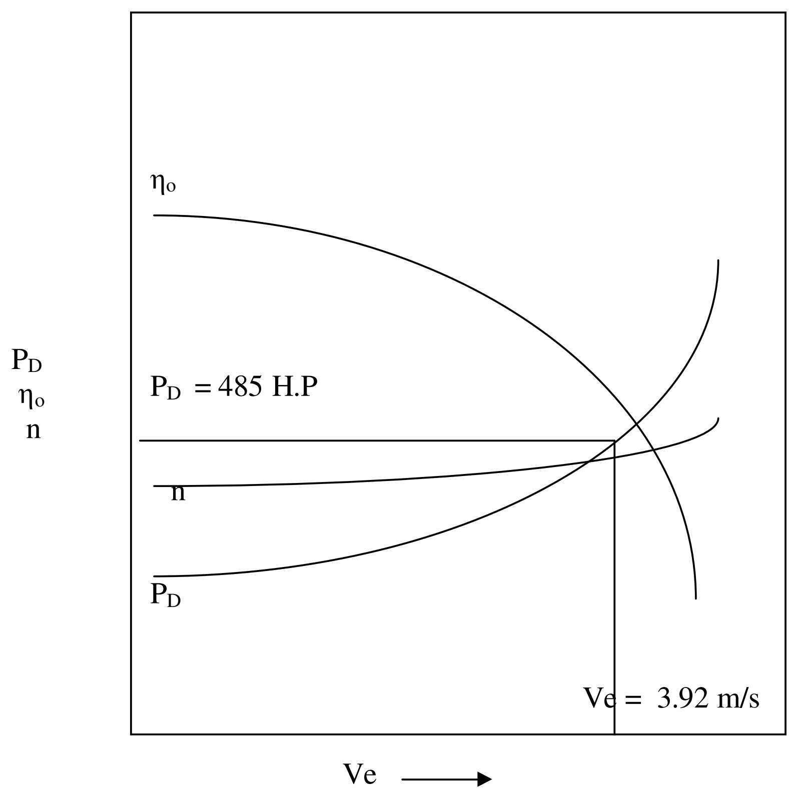
Find also the speed corresponding to $P_D =$ 485 H.P .

Solution :

Td	1.015	0.888	0.851	
λ	0.420	0.460	0.210	(intersection with H/D=0.75)
n	4.975	4.172	3.705	
P_D	785	438	299	

$Nw = Km\ 2.0\ \pi\ \rho\ n^3 D^5$, $P_D = Nw/ 75$

η p	0.536	0.5697	0.585



Example 7 :

It is required to determine the tow rope pull f(Ve) for a tug has 2 B3.65 propellers , works in fresh water , the following are given :
M = 508 Kp.m , D = 1.388 m , H/D = 1.2 , t = 0.14 , w = 0.194

The free running resistance Ro is given as f(Ve) .

Ve	1	2	3	4	5	m/s
Ro	185	350	545	785	1210	Kp

Ro + T = S (1 - t) Np   Np is the number of propellers

This problem may be solved by assuming some arbitrary values of Td and from intersection with H/D curves Km , λ , could be found .

Td	0.60	0.70	0.80	1.00	1.20	1.50	2.00	3.00
Km	0.0415	0.0464	0.0506	0.0572	0.0682	0.0692	0.0757	0.0824
λ	0.78	0.715	0.657	0.563	0.429	0.421	0.324	0.226

$$n = \sqrt{\frac{M}{102.0 x D^5 x Km}}$$ M 2 π n = Nw ,   Ve = λ n D

n	4.905	4.640	4.440	4.152	3.974	3.796	3.628	3.476	rps
Ve	5.28	4.580	4.025	3.225	2.696	2.160	1.622	1.089	m/s

S = Td **2 ρ D**2 Ve**2

S	1972	2019	2037.5	2043	2056.75	2062.86	2067.95	2097	Kp

P_D = 2 π n M / 75

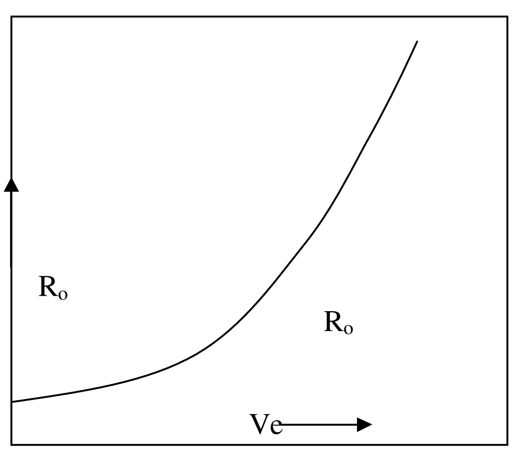
P_D	209	197.7	189.2	177	169.3	161.8	154.5	148.1	H.P	
Ro	1410	1003	800	600	466	380	285	200	Kp	Ro = f(Ve)

T = Np S (1 - t) - Ro = Np S (1 - 0.17) - Ro

T	1255	2060	2620	2875	3060	3186	3320	3410	Kp

From Vs = Ve / (1 - w)

Vs	6.551	5.682	4.994	4.001	3.345	2.680	2.012	1.351	m/s



Example 8:

It is required to determine the bollard pull for the given propellers of the previous example . (t for bollard pull conditions = 0.05)
From S-λ and Nw- λ diagrams at $\lambda = 0.0$ read Km and Ks at H/D = 1.2

Km = 0.0952 , Ks = 0.53 T = S (1 - t) Np

$$n = \sqrt{\frac{508}{102xKmx\,D^5}} = \sqrt{\frac{508}{102x0.0952x\,1.38^5}} = 3.235 \quad \text{rps}$$

S = Ks ρ n**2 D**4 = 2050 Kp T = 2050 (1 - 0.05) 2 = 3894 Kp

Similar calculations for P_D constant and n constant can be done .

Example 9:

A single screw ship has a B4.55 propeller of 2.88 m diam. Determine the pitch of the propeller which makes it absorb 2450 H.P at 12 Knots speed of ship if n = 200 rpm , w = 0.25 , find also ηp .

Solution :

In this example we are searching for the operation point of propeller .
Ve = 12 x 0.514 (1- 0.25) = 4.626 m/s

$$Pn = \frac{n}{Ve^2}\sqrt{\frac{Nw}{2\pi\rho Ve}} = \sqrt{\frac{Km}{\lambda^5}}$$

$$Pn = \frac{n^2}{Ve}\sqrt{\frac{2450x75}{2x3.14x104.8x4.626}} = 1.209$$

$$\lambda = \frac{Ve}{nD} = 0.4824$$

From intersection between Pn & λ $\rightarrow$ H/D , ηp , and Ks could be found .

S = Ks ρ n**2 D**4

= 0.26 x 104.8 x 3.33**2 x 2.88**4 = 20787 Kp

ηp = S Ve / 2450 x 75 = 0.523

H/D = 0.97 , Ks = 0.26 , ηp = 0.52 (from chart)

Cavitation of Propellers

The cavitation described as local boiling resulting in formation of bubbles and region of vapor within the liquid . This is a direct result of reducing local pressure to or near the vapor pressure of the liquid .

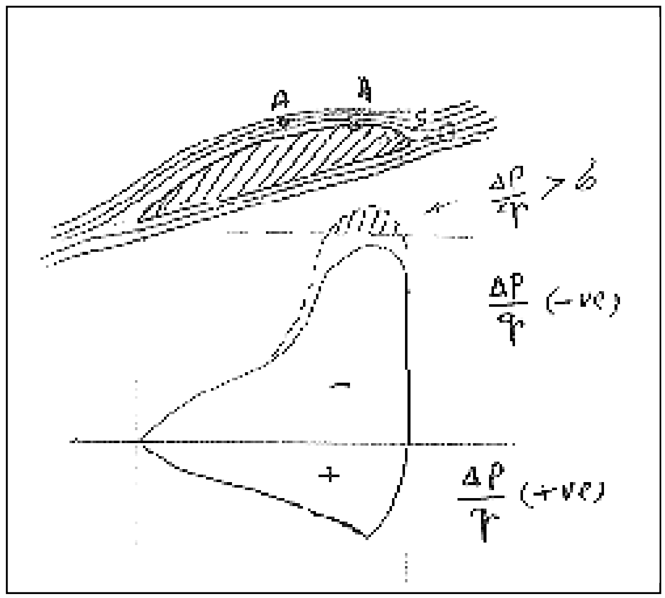
Consequences of Cavitation :

Destruction of propeller material by mechanical erosion and chemical corrosion .

The Cavitation Number :

The cavitation number is the criterion by which the cavitation is controlled , it gives the limit of propeller loading after which the water will start boiling at the back of the propeller causing high dynamic forces on the blades which change and varies periodically and result in eroded and corroded blades and finally in damaged propeller and loss of efficiency .

In the shown figure , the total energy far ahead of the section will be :



$$\frac{P}{\gamma}+\frac{V^2}{2g}=constant$$

At point A in the stream ;

$$Pa+\rho\frac{Va^2}{2}=constant$$

But at point O little away from the nose of profile :

$$Po+\rho\frac{Vo^2}{2}=constant$$

$\Delta P = Pa - Po = 0.5\ \rho\ (Vo^2 - Va^2)$

If $Va > Vo \quad \therefore\ Pa < Po \quad \& \quad \Delta P$ = negative

At point S near the nose , the flow divides , from which a part is turning through 90 degrees , losing all its velocity and momentum in the direction of motion along the stream line ($Vs = 0.0$)

$q = 0.5\ \rho\ Vo^2$ is called the stagnation pressure , s is called stagnation point .

At any point 1 on the back , P1 is the pressure & V1 is the speed .

$$P1 = Po + 0.5\,\rho\,(Vo^2 - V1^2) = Po + \Delta P$$

$\therefore\ \Delta P = -Po \qquad$ if $P1 = 0.0$

Since the water cannot support tension , the flow will break down at this point with bubble formation and cavitation occurrence .

In practice , this situation will come somewhat earlier because P1 cannot reach zero but only till the vapor pressure Pv at which the it starts boiling .
The criterion for such condition will be that :

$$Pv \leq Po + \Delta P$$
$$\therefore \quad \Delta P \geq Pv - Po$$

Dividing by q $\rightarrow$ $\quad \dfrac{\Delta P}{q} \leq \dfrac{Po - Pv}{q} ......and..the..term.. \dfrac{Po - Pv}{q} = \sigma$

σ is called the cavitation number .
For any design case , σ can be calculated .

$$\sigma = Pa + \gamma\ (h - r) - Pv / (0.5\ \rho\ (Va^2 + \omega^2\ r^2\ )$$

Types of Cavitation :

It is better to call it phases of cavitation , there are mainly four phases of cavitation , that depend on screw loading and angle of attack .

1 . Face Cavitation :
It happens if the angle of attack becomes negative due to wake inequality .

2. Sheet Cavitation :
It happens as a consequence of increasing α (the angle of attack) which results in traveling of stagnation point to the face side and a flow around the leading edge with a very high velocity will take place .

The tip vortices will be influenced by this low pressure until approaches the vapor pressure which leads to starting cavitation . In this stage it is a slightly separated sheet from the tip and no influence on thrust (It looks like a silver sheet on the blade starting from the leading edge)

3. Bubble Cavitation :
For increased loading on the blade the bubbles start appearing on the back and the dynamic forces start influencing on the blade .

4. Cloud Cavitation :
By overloading the blade , a formation of eddies in the cavitated zone , the cavities appear and collapse at the blade surface causing a strong erosion .

Effects of Cavitation on Screw Characteristics :

Several charts for cavitation effect on screw are made by Burril and others .
The thrust of cavitated propeller drops drastically due to escape of pressure from the high pressure side to the low pressure side of the propeller through the cavities .
The structural strength of the propeller falls too because of the lost area and material of the propeller , high stresses exert on the blades which leads finally to a fully damaged propeller blades.
The area of propeller blades is determined from the cavitation charts in such a way that the absolute values of pressure drop on the back of propeller ,divided by the stagnation pressure (q) , (be always less than the cavitation number σ .

Calculation of Blade Area For a Cavitation-free Propeller

The suitable area for a cavitation-free propeller may be calculated according to the diagrams given by Burill & V. Manen for cavitation limits and also according to the diagrams given by Schoenherr .

1 - The method of Burill & V. Manen .

The cavitation diagrams of this method are given in the form of a relationship between specific load number of propeller and the cavitation number at different pitch ratios but for specific number of blades , the method could be summarized as follows :

.

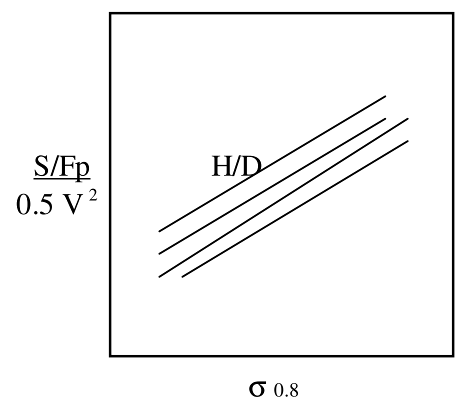
1. Determine the cavitation number $\sigma_{0.8}$:

$$\sigma_{0.8} = \frac{Po - Pv - 0.8\, R\, \gamma}{\rho \frac{V^2}{2}} = f$$

For safety reasons a factor of safety of 0.25 is considered ($f = 1.25\ \sigma_{0.8}$) .

$$\sigma_{0.8} = f / 1.25$$

Po = Static pressure at the center line of propeller
Pv = Vapor pressure of water
R = radius of propeller
S = Thrust
Fp = Projected area



2 - At H/D , intersection with $\sigma_{0.8}$ Find $\frac{S/Fp}{0.5\, V^2}$

3 - Calculate Fp

4 - Calculate Fa required

$$Fa\ required = Fp / (1.067 - 0.229\ H/D)$$

5 - Calculate Fa given $= Fa/F \times \pi\, D^{**}2 / 4$

6 - At different given area ratios , draw the curves of (Fa required) and (Fa given), the zone in which the required area is higher than the given area means that the propeller is liable for cavitation due to the insufficient area given which will increase the negative pressure intensity at the back of the blade to be at or around the vapor pressure .

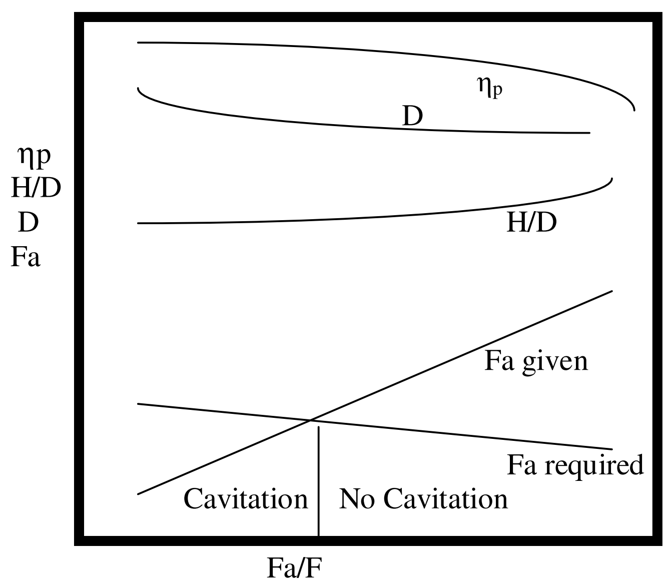
:

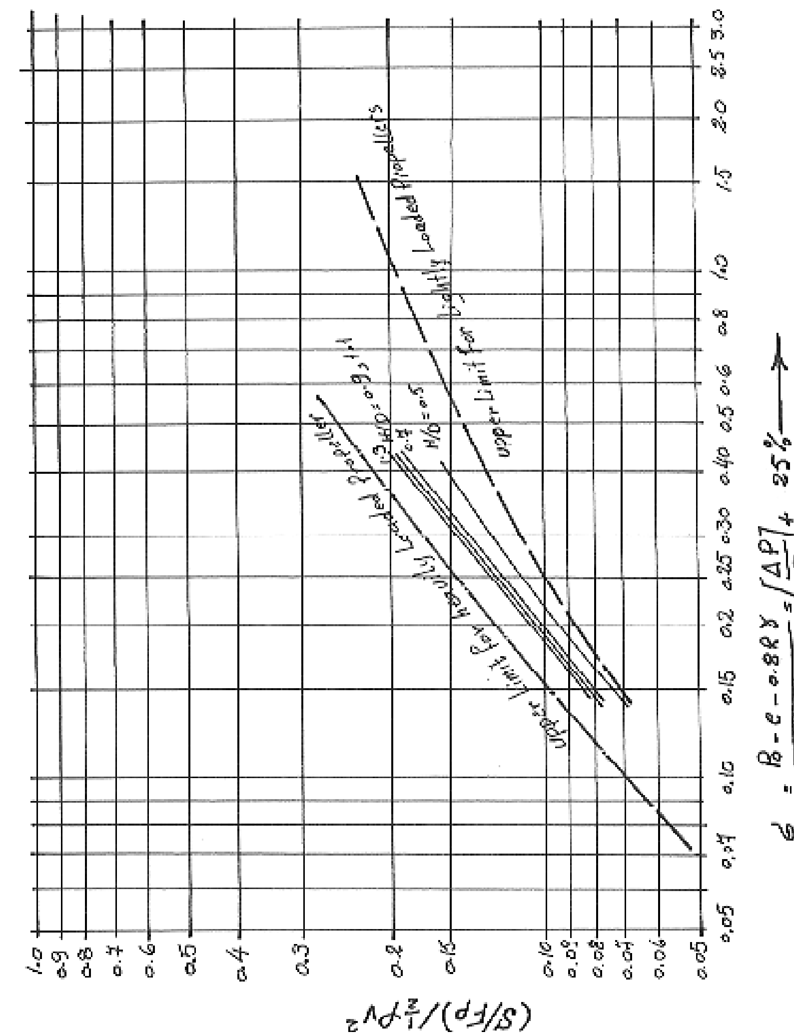
Scheme for Calculation

Fa/F	Po	Po-Pv	0.8R γ	Numerator	H/D	Ve^2	U	U^2	V^2

$U = 0.8 \pi D n$ $\qquad$ $V = \sqrt{Ve^2 + U^2}$ $\qquad$ $\sigma_{0.8} = f/1.25$

Fa/F	Denominator	f	$\sigma_{0.8}$	$S/Fp/0.5 \rho V^2$	Fp	Fa required	Fa given





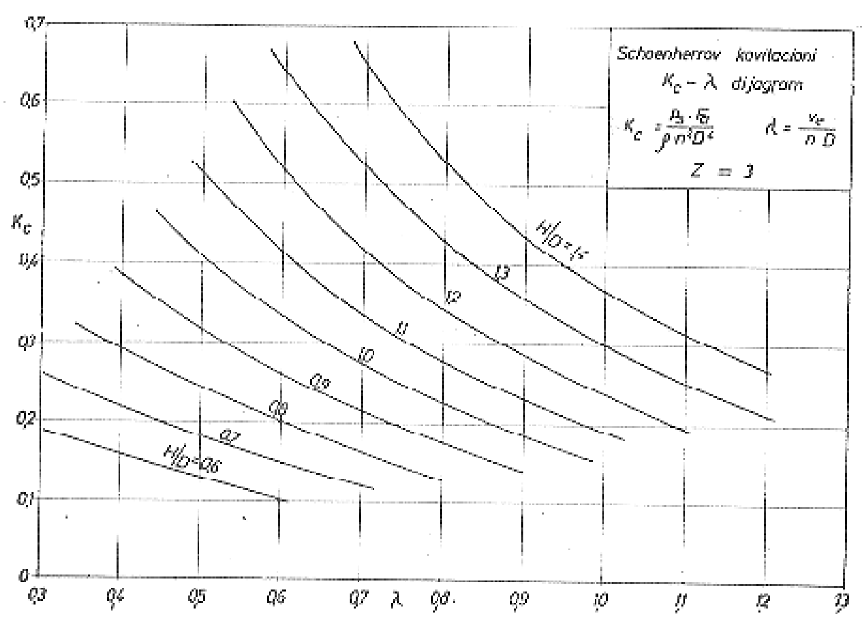
Limits of Cavitation According to Burill , V. Manen For Z = 3

2 - The Method of Schoenherr :

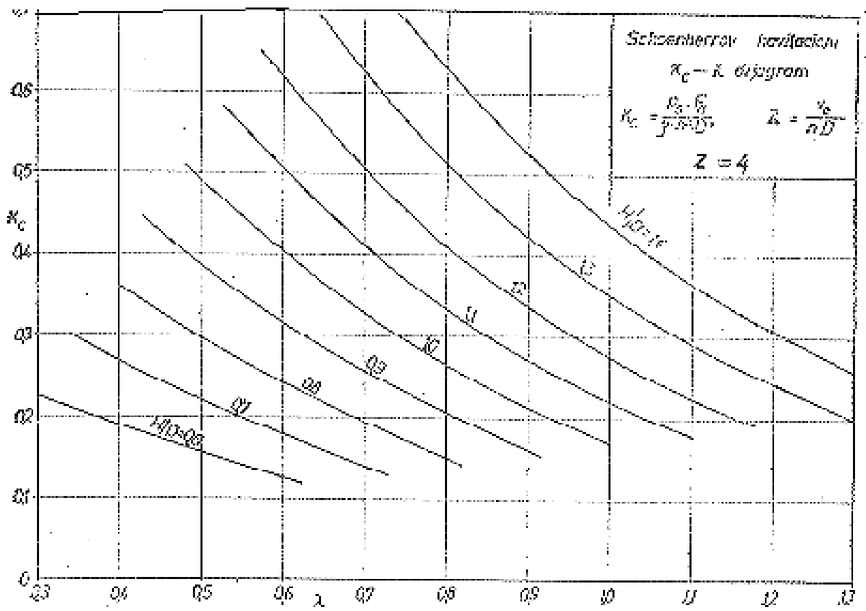
Using Schoenherr cavitation charts , it is possible to determine the required expanded area for a cavitation-free propeller , the procedure is as follows :

$$S / Fa = Ks . Ps / (f . Kc)$$
$$Kc . f = Ps . Fa / (\rho \; n^2 \; D^4)$$
$$Ps = \gamma (T - h - R + Hv) + Po - Pv$$
$$Fa = Kc \; \rho \; n^2 \; D^4 \; f / Ps$$

S = Thrust Kp
Fa = Expanded area sq. m
f = Factor of safety (1.3 to 1.6)
Kc = Expanded area coefficient
Ps = Absolute pressure , reduced by vapor pressure at the tip of propeller blade (Kg/m ^{2})
λ = advance coefficient
T = Draft of the ship , m
h = Height of propeller axis above keel , m
R = Radius of propeller , m
Hv = Wave height at ship's stern , m
Po = Atmospheric pressure (Kg/m ^{2})
Pv = Vapor pressure (Kg/m ^{2})
γ = Specific weight of water .

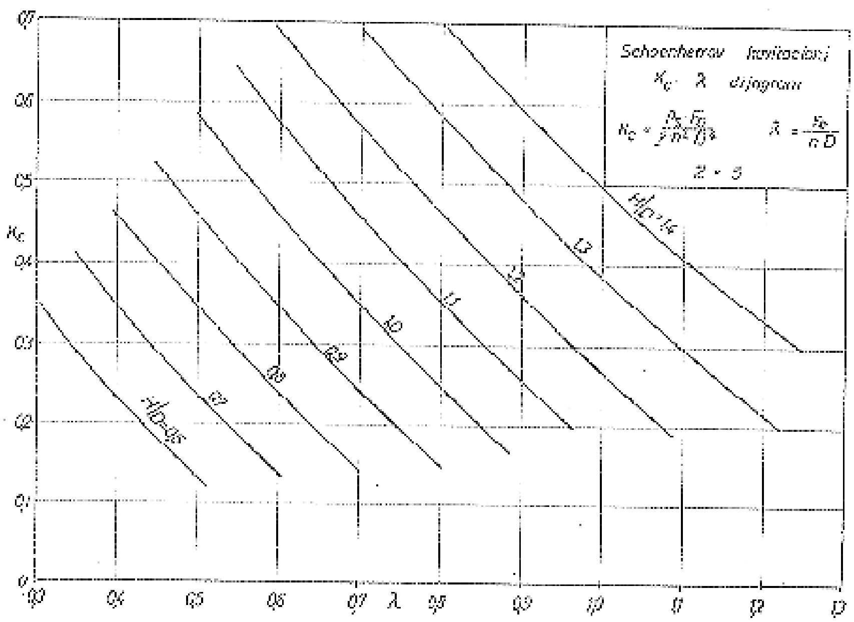


Schoenherr Cavitation Diagram for Z = 3



Schoenherr Cavitation Diagram for Z= 4

Schoenherr Cavitation Diagram for Z= 5



Some Design Considerations for Propellers

1 - The choice of number of blades :

It is dependent on vibration and propeller loading and the efficiency .

Two blades propellers are used in auxiliary engines for sailing ships and sporting boats .

Three blades are not suitable for 6 or 9 cylinders engines , they are suitable for single screw ships with highly loaded propellers , they have the minimum risk of cavitation .

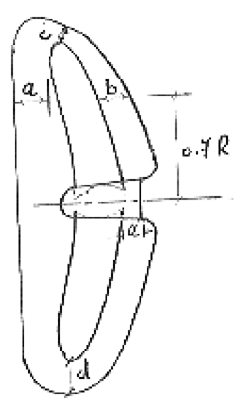
Four blades are not suitable for 4 and 8 cylinders , they are used for Twin screw ships with small diameter and also for single screw with small diameter .

Five blades are not suitable for 10 cylinders engines , favorable for avoiding vibration , used for large tankers .

2 - Propeller Clearances :

The clearances between propeller and hull are of vital importance , the propeller as a source of excited vibrations must be clear of the hull to avoid the transmission of vibratory pulses to the hull which may meet any other source of excitation and cause together a resonant critical vibration and noise problems .
The minimum clearances recommended by different maritime authorities are as follows :

	LR	DNV	NPL	NSMB	GL
a	0.08 ~ 0.15 D	(0.72 t/l) D	0.08~0.15 D	0.08 ~ 0.12 D	0.1 D
b	0.15 D	0.11(1- φ)	0.20 D	0.15 ~ 0.20 D	0.18 D
c	0.08 D	0.08 D	0.08~ 0.10 D	0.10 ~ 0.12 D	0.17 D
d	--------	0.03 D	0.02~ 0.03 D	0.03 D	0.04 D



φ = Angle of run of waterline 0.5 R above the propeller CL .
t/l = Thickness ratio of rudder .

The W.B. Polynomials of Propeller Design

The application of computers in preliminary ship design studies is rapidly increasing from which the ship size , dimensions , and powering could be determined . In this respect the hydrodynamic aspects such as resistance , wake and thrust deduction, and propeller characteristics are of importance and must be computerized .
The propeller date are given in a computerized method through the W.B. Polynomials which could be easily handled by computers .
The propeller thrust and torque coefficients are given in a form of polynomials as follows :

$$Ks = f(\lambda , H/D , Fa/F , Z , Rn) = S / \rho n^2 D^4$$
$$Km = f(\lambda , H/D , Fa/F , Z , Rn) = M / \rho n^2 D^5$$

$$\eta_o = (Ks/Km)\ (\lambda/2\pi)$$

The cavitation – free blade area ratio Fa/F may be calculated using Keller equation :

$$Fa/F = \frac{(1.3+0.3Z)S}{(Po-Pv)D^2} + K$$

The effect of Reynolds number has been taken into account by using the method developed by Lerbs , from which the blade section at 0.75R is assumed to be equivalent for the whole blade .
The Rn in the polynomials is assumed = 2E06 , if the Rn for any design proplem differs , a correction has to be made to Ks , Km .

The W.B. Polynomials are valid for designing propellers of 2 , 3 , 4, 5 , 6, and 7 blades .

$$Ks = \sum_{I=1}^{I=39} C_{si}\ \lambda^{si}\ (H/D)^{ti}\ (Fa/F)^{ui}\ Z^{vi}$$

$$Km = \sum_{I=1}^{I=47} C_{mi}\ \lambda^{s`i}\ (H/D)^{t`i}\ (Fa/F)^{u`i}\ Z^{v`i}$$

The additional polynomials for Ks & Km corrections due to Rn differing from 2E06 are given below :

$$\Delta Ks = \sum_{K=1}^{K=9} Cs1_k\ (\log Rn - 0.301)^{ak}\ \lambda^{BK}\ (H/D)^{ck}\ (Fa/F)^{dk}\ Z^{ek}$$

$$\Delta Km = \sum_{K=1}^{K=13} Cm1_k\ (\log Rn - 0.301)^{a`k}\ \lambda^{b`K}\ (H/D)^{c`k}\ (Fa/F)^{dk}\ Z^{e`k}$$

$$Rn = V_{0.75R}\ L_{0.75R} / \nu$$

$V_{0.75R}$ = Resultant speed at the blade element at 0.75R
$L_{0.75R}$ = Chord length oft the blade element at 0.75R
ν = Kinematic viscosity of water

The values of polynomials coefficients and exponents are given in the following tables :

i	Cs_i	s_i	t_i	u_i	v_i
1	+0.00880496	0	0	0	0
2	-0.204554	1	0	0	0
3	+0.166351	0	1	0	0
4	+0.158114	0	2	0	0
5	-0.147581	2	0	1	0
6	-0.481497	1	1	1	0
7	+0.415434	0	2	1	0
8	+0.0144043	0	0	0	1
9	-0.0530054	2	0	0	1
10	+0.0143481	0	1	0	1
11	+0.0606826	1	1	0	1
12	+0.0125894	0	0	1	1
13	+0.0109689	1	0	1	1
14	-0.133698	0	3	0	0
15	+0.00638407	0	6	0	0
16	-0.00132718	2	6	0	0
17	+0.168496	3	0	1	0
18	-0.0507214	0	0	2	0
19	+0.0854559	2	0	2	0
20	-0.0504475	3	0	2	0
21	+0.010465	1	6	2	0
22	-0.00648272	2	6	2	0
23	-0.00841728	0	3	0	1
24	+0.0168424	1	3	0	1
25	-0.00102296	3	3	0	1
26	-0.0317791	0	3	1	1
27	+0.018604	1	0	2	1
28	-0.00410798	0	2	2	1
29	-0.000606848	0	0	0	2
30	-0.0049819	1	0	0	2
31	+0.0025983	2	0	0	2
32	-0.000560528	3	0	0	2
33	-0.00163652	1	2	0	2
34	-0.000328787	1	6	0	2
35	+0.000116502	2	6	0	2
36	+0.000690904	0	0	1	2
37	+0.00421749	0	3	1	2
38	+0.0000565229	3	6	1	2
39	-0.00146564	0	3	2	2

i	Cm_i	s_i`	t_i`	u_i`	v_i`
1	+0.00379368	0	0	0	0
2	+0.00886523	2	0	0	0
3	-0.032241	1	1	0	0
4	+0.003447	0	2	0	0
5	-0.0408811	0	1	1	0
6	-0.108009	1	1	1	0
7	-0.0885381	2	1	1	0
8	+0.188561	0	2	1	0
9	-0.00370871	1	0	0	1
10	+0.00513696	0	1	0	1
11	+0.0209449	1	1	0	1
12	+0.00474319	2	1	0	1
13	-0.00123408	2	0	1	1
14	+0.0038388	1	1	1	0
15	-0.0269403	0	2	1	1
16	+0.0558082	3	0	1	0
17	+0.0161886	0	3	1	0
18	+0.00318086	1	3	1	0
19	+0.015896	0	0	2	0
20	+0.0471729	1	0	2	0
21	+0.0196283	3	0	2	0
22	-0.0502782	0	1	2	0
23	-0.030055	3	1	2	0
24	+0.0417122	2	2	2	0
25	-0.0397722	0	3	2	0
26	-0.00350024	0	6	2	0
27	-0.0106854	3	0	0	1
28	+0.00110903	3	3	0	1
29	-0.000313912	0	6	0	1
30	+0.0035985	3	0	1	1
31	-0.00142121	0	6	1	1
32	-0.00383637	1	0	2	1
33	+0.0126803	0	2	2	1
34	-0.00318278	2	3	2	1
35	+0.00334268	0	6	2	1
36	-0.00183491	1	1	0	2
37	+0.000112451	3	2	0	2
38	-0.0000297228	3	6	0	2
39	+0.000269551	1	0	1	2
40	+0.0008365	2	0	1	2
41	+0.00155334	0	2	1	2
42	+0.000302683	0	6	1	2
43	-0.0001843	0	0	2	2
44	-0.000425399	0	3	2	2
45	+0.0000869243	3	3	2	2
46	-0.0004659	0	6	2	2
47	+0.0000554194	1	6	2	2

Coefficients of polynomial for effect of Reynolds number on thrust coefficient Ks

k	$CS1_k$	a_k	b_k	c_k	d_k	e_k
1	+0.000353485	0	0	0	0	0
2	-0.00333758	0	2	0	1	0
3	-0.00478125	0	1	1	1	0
4	+0.000257792	2	2	0	1	0
5	+0.0000643192	1	2	6	0	0
6	-0.0000110636	2	2	6	0	0
7	-0.0000276315	2	2	0	1	1
8	+0.0000954	1	1	1	1	1
9	+0.0000032049	1	1	3	1	2

Coefficients of polynomial for effect of Reynolds number on torque coefficient Km

k	$Cm1_k$	a_k`	b_k`	c_k`	d_k`	e_k`
1	-0.000591412	0	0	0	0	0
2	+0.00696898	0	0	1	0	0
3	-0.0000666654	0	0	6	0	0
4	+0.0160818	0	0	0	2	0
5	-0.000938091	1	0	1	0	0
6	-0.00059593	1	0	2	0	0
7	+0.0000782099	2	0	2	0	0
8	+0.0000052199	1	2	0	1	1
9	-0.00000088528	2	1	1	1	1
10	+0.0000230171	1	0	6	0	1
11	-0.00000184341	2	0	6	0	1
12	-0.00400252	1	0	0	2	0
13	+0.000220915	2	0	0	2	0

Problems on Powering and Propulsion of Ships

1. A ship at full speed has an effective power of 6.087E06 wat . , The hull efficiency is 0.98 , the open water propeller efficiency is 0.69 , relative rotative efficiency is 0.98 . Find the quasi propulsive efficiency and the shaft power .

2. Given : $\eta_o = 0.582$, $\eta_R = 0.99$, $w = 0.30$, $t = 0.20$ find η_B , and η_D ..

3. The propellers of a twin screwed ship operate in a wake of 2 knots , the ship is moving ahead at 21 knots , the effective power is 6720 H.P.
If the thrust developed by each propeller is 26.5 ton , Calculate :
   a. The thrust horsepower for each propeller
   b. The hull efficiency

4. For a ship , the following are given :
   $V_e = 10.36$ Knots , $P_D = 2800$ Kw , $\eta_B = 0.656$, $C_B = 0.78$.
Find the total resistance , effective power and quasi propulsive efficiency.

5. A ship has a speed of 15 Kn. works in a wake of 4.5 Kn. , the thrust deduction factor = 0.20 , engine torque is 1110 Kp.m and the propeller rotates at 150 rpm . If the relative rotative efficiency is 0.99 , the quasi propulsive efficiency is 0.70 , Calculate the thrust of the propeller of such ship .

6. The brake power of a ship's engine is 20000 Kw. , its specific fuel consumption is 160 gr/kw/hr , the number of sea days is 200/year and the fuel price is $140/ton , If an improvement in propulsive efficiency of 10% is attainable , determine the annual save in fuel expenses .

7. A ship is working through a route of 20000 sea miles at an average speed of 20 Kn. If the S.F.C of the engine is 150 gr/hp/hr , the propeller thrust is 6000 Kp , w= 0.31 , How much will be the behind efficiency of the propeller assuming sea allowance of 5% , transmission efficiency of 0.98 with gearing and mechanical efficiency of 0.98 and total fuel consumption /trip = 1640 ton .

8. A ship of 12400 tons displacement is 120 m long , 17.5m beam and floats at a draft of 7.5m . The propeller has a face pitch ratio of o.75 and an expanded area ratio of 0.50 , when turning at 100 rpm produces a ship's speed of 12 kn. with a real slip of 30% . Calculate the apparent slip , pitch and expanded area of the propeller .($w=0.50C_B-0.05$) .

9. A propeller 4.6m diam has a pitch of 4.3m and boss diameter of 0.75 m . The real slip is 28% at 95 rpm , calculate the speed of advance , thrust and thrust power .

Naval Architecture Examination

1. State when we can decide either single or twin screw propulsion ? (4 degrees)

2. What are the advantages and disadvantages of C.P. propellers ? (4 degrees)

3. State the application condition of :
   a. Accelerating nozzle propeller,
   b. Decelerating nozzle propeller . (4 degrees)

4. What are the main considerations in choosing and designing screw propellers? (4 degrees)

5. What is the advantage of a skewed propeller blade ? (4 degrees)

6. Why a V.S.P must has an even number of blades ? (4 degrees)

7. A ship has two fuel tanks for M.E. , each of 15 ton capacity , works through a route of 1000 S.M. at a speed of 10 knots .
With a sea allowance of 5% , reserve fuel of 10% , calculate the number of trips the ship can perform if the engine power is 500 H.P and S.F.C. is 150 Gr/BP/Hr . (6 degrees)